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Cave Development in Strata of Ordovician-and Silurian-Devonian-Age in Highland County, Virginia

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CAVE DEVELOPMENT IN STRATA OF ORDOVICIAN- AND SILURIAN-DEVONIAN-AGE IN HIGHLAND COUNTY, VIRGINIA

by

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ABSTRACT

CAVE DEVELOPMENT IN STRATA OF
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IN HIGHLAND COUNTY, VIRGINIA

Carol Ann Peterson
Old Dominion University, 2007
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Picturesque Highland County, Virginia, also known as "Virginia's Little Switzerland", is characterized by high mountains, tranquil rivers, and hundreds of caves. This study determines how geologic structures and processes control speleogenesis, or cave development, in the county. Solutional caves in Highland County are found in Ordovician limestones and dolostones and in Silurian- to Devonian-age limestones. Despite the lithologic and structural differences between the strata, caves in both sections tend to be similarly joint-controlled in directions of both regional strike (N40°E), dip (northwest or southeast), or in fractures intersecting at 60 and/or 120 degrees. Brittle failure, including fractures and faults induced by folding, appears to be the most prominent controlling factor of speleogenesis in Highland County.

Despite the findings of other studies indicating that branchwork cave patterns dominate most karst aquifers by frequency and total cave length, fissure-type caves are the most frequent pattern in Highland County and maze network caves are the most predominant pattern by total cave length. Fissure-type caves tend to be very short with most occurring up to 20′ (6 m) long. Slot fissures are more canyon-like and tend to be longer with most being either 21-40′ (6-12 m) long or 101′-200′ (31-61m) long. Branchwork caves tend to be longer with most ranging from 201′-300′ (61-91 m) long, while maze networks tend to be the longest, with most ranging from 801′-2000′ (244-610 m) long. Though cave patterns in Highland County do not entirely reflect predominant cave patterns found worldwide, the overall trend of cave lengths is similar to that found throughout Virginia.

In addition to the aforementioned cave patterns found in Highland County, pits and rooms also constitute a large proportion of the cave types in the county, evidence of the vadose recharge that most affects the subsurface dissolution. Approximately 92% of Highland's caves

show vadose cave development, while only 4% show active phreatic development, and 5% show characteristics of both active vadose and phreatic development. These observations are consistent with the fact that fissures, slot fissures, pits, and rooms- the types of caves most frequently found in Highland County- all form in areas of vadose recharge.

This thesis is dedicated to:

my Husband: How could I have done this without your patience, support, love, and Geology Geek jokes? Without you, I'd *still* be working on my Associate's! Thanks for not walking in front of me or behind me, but walking beside me. I love you.

my terrific children: My proudest accomplishment is being your mom (and stepmom). I love you more than anything. Remember- sometimes the hardest path and the right path are the same. (That probably means you will have to learn how to climb). I hope I've taught you well- that it isn't always strength that will get you to where you want to be... it's persistence.

my parents: ...for showing me how to persevere by unknowingly presenting me the challenge to prove to you that I could do it. I love you dearly.

my brothers: ...my bestest friends. I am very proud of you and all of your accomplishments. I am proud to be your big sister, but mostly proud that you are my wonderful brothers.

my extended family: I joke and say that I have a Family Forest instead of a Family Tree. I wouldn't want it any other way, nor would I want to be a part of any other Forest.

my closest friends:...I believe that we are who we are because of the decisions we make and the people that we meet along the way. I'm grateful everyday that our paths have crossed.

And finally to:

my Grandparents, who walk the Other Side Camp. Thanks for instilling in me the appreciation, curiosity, and respect for the Great Outdoors and for encouraging me to learn Mother Earth's secrets. Only you understand what it has truly taken for me to get Here. I miss you every day.

ACKNOWLEDGMENTS

I would like to thank the Virginia Speleological Survey and Dr. Rich Whittecar at Old Dominion University for allowing me the opportunity to pursue this project. I would also like to thank the dedicated members of the Highland County Cave Survey—their perseverance has provided an enormous collection of data over the years, which is what spurred the original interest to "do something" with it. This study is but a scratch on the surface of the many projects yet to come. I would like to thank Chris Woodley, a member of the HCCS –without him, I would still be entering data and manually measuring lengths off of cave maps. His GIS and software knowledge made this project more efficient and opened a door to many future cave studies. Thanks also to Brett Waller for pointing me in the right direction... more than once. Several mapping folks, including Lee Avary and Dave Matchen at the West Virginia Geologic and Economic Survey and Gerry Wilkes at the Virginia Division of Mineral Resources, were a terrific help and provided map data and insight into Appalachian stratigraphy and lithology. Thanks so much!

I would especially like to thank Rick Lambert. Although the desire to choke him or push him down a pit arose frequently, this project would not have been possible without him. His mountaineering experience only got us lost a few times and his generous dose of invincibility enabled him to retrieve rock samples over ominous pits where I wouldn't have dared hover untethered. It has been a memorable Journey, my Friend.

And finally, I would like to express my sincere gratitude and appreciation to the cave owners of Highland County, Virginia who allowed us access onto their property. Without the trust and permission of cave owners like you, understanding caves would be an elusive frontier and we cavers would be terribly bored.

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DISCLAIMER

This document is not intended to disclose cave names, cave locations, or names of cave owners. Reference to particular cave names may be addressed by cave numbers designated by the Virginia Speleological Survey (VSS). Additionally, maps, pictures, and figures may be generalized as a result of specifications outlined in a contract between the author, the Highland County Cave Survey (HCCS), and the VSS. Requests for more specific data resulting from this study may be submitted in writing to the VSS at:

Virginia Speleological Survey
572 Spruce Street
Monterey, Virginia 24465

INTRODUCTION

Highland County, Virginia, is located in west-central Virginia in the Valley and Ridge physiographic province (Figure 1). Since 1991, dedicated members of the Highland County Cave Survey (HCCS) have located, surveyed, and mapped approximately eighty percent of previously reported caves and have found and mapped numerous unreported caves. To date, 260 caves have been mapped with the longest known cave yielding over 7.0 miles (11.3 km) of passage, and the deepest at -520 feet (158 m) from the surface. Several talus and tectonic caves exist in sandstone terrain in the area; however, the majority of the county's caves are solutional caves in carbonate rocks resulting in approximately 50% of the county's area being karst terrain (underlined terms- please see Appendix A- Glossary of Terms). Cave formation, or speleogenesis, is controlled by many different factors including geologic structures, hydrology, lithology, and topography. Understanding cave development is critical to understanding soil and bedrock stability, contaminant migration in aquifers, and hydrologic and geomorphic conditions of karst regions (Palmer, 1991). Studying cave morphology, cave patterns,

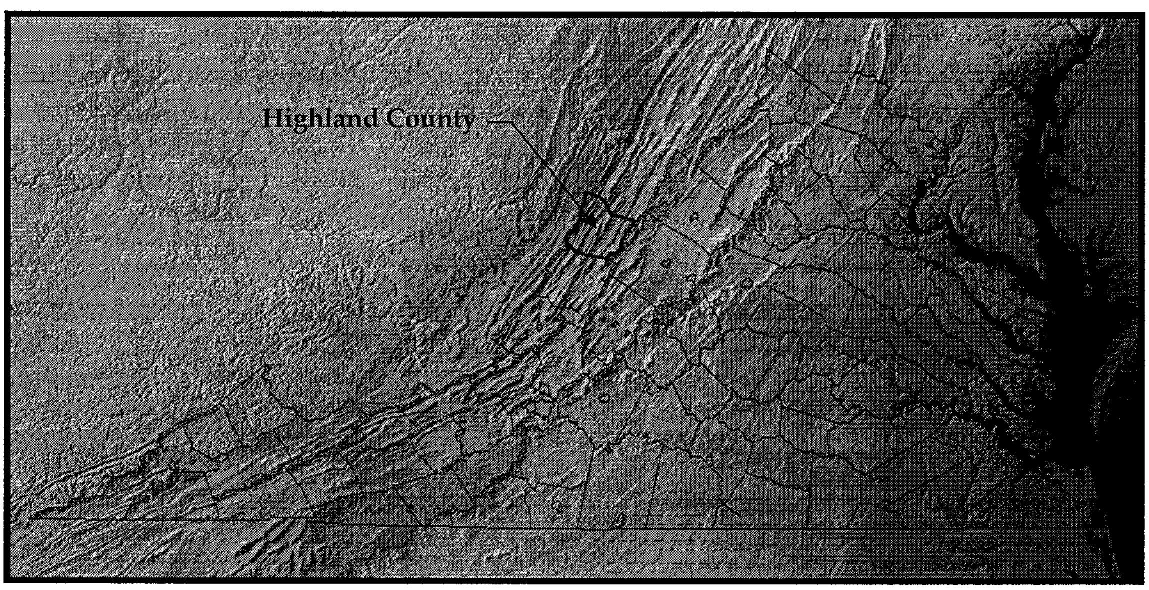


Figure 1. Map of Virginia counties and topography.
(After U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2007).

The format for this paper is modeled after the *Journal of Cave and Karst Studies*, a publication of the National Speleological Society.

predominant passage orientation, cave densities, and spatial relationships are fundamental in the quest to understand cave development and controls in Highland County.

The main purpose of this study is to offer insight into the controls of speleogenesis in the area. This in turn will provide a foundation for future karst, hydrologic, and hazard assessment studies as well as local water supply and hazard planning in Highland County. Additionally, insight into potential locations of undiscovered cave areas in Highland County will be established. Furthermore, information resulting from this study will be used to update the cave and karst databases maintained by the Virginia Speleological Survey (VSS) and the HCCS.

BACKGROUND

Geology and Structures

The Valley and Ridge physiographic province is the classic example of a folded and faulted foreland mountain system (Faill and Nickelsen, 1999). Today's Appalachian Mountains are remnants of mountains that began forming approximately 450 million years ago, first starting with the Taconic and Acadian mountain building events, or orogenies. Then, during the Pennsylvanian and Permian periods approximately 250-300 million years ago, the final orogenic event for the Appalachians occurred when proto-Africa was thrust over eastern North America during the Alleghenian Orogeny (Fichter, 1999; PRI, 2006). During this mountain-building episode, compressional stresses acted upon the land masses, causing deformation and uplift of the eastern North American margin. The resulting plastic strain on the land masses caused folding (bending) while the brittle strain caused fracturing (breaking) of the formerly horizontal Paleozoic sedimentary layers (USGS CVO, 2007).

Plastic strain results in folded rock, which is rock that has been compressed or pushed into a series of arches (anticlines) and troughs (synclines; Plummer and McGeary, 1988). When the rock mass exceeds its limitation of plastic strain, fracturing occurs, which is often the case in folded rocks (Twiss and Moores, 1992). Fractures with visible displacement are "faults" and fractures with little or no displacement are "joints". Many adjacent joints that are approximately parallel to one another and are oriented in the same direction are collectively known as a "joint set". Several joint sets of differing directions may be present in the same outcrop and where two or more different sets intersect at constant or near constant angles, they form "joint systems" (Twiss and Moores, 1992; Plummer and McGeary, 1988; Klimchouk and Ford, 2000). Fractures that have been widened by dissolution are "fissures" (Twiss and Moores, 1992).

Structural geology primarily controls speleogenesis, or cave formation, by the folding, faulting, and eroding of rocks and secondarily by planar fractures such as joints, bedding planes, and faults (Sasowsky, 1999). In most sedimentary rocks (such as limestone and dolostones), the most common system of jointing is a rectangular system of tension jointing. This occurs when systematic joints (approximately equi-spaced joints) run parallel to strike while cross joints are approximately perpendicular to the systematic joints. One idea behind the conception of this pattern is that the main trend (systematic joints) are approximately perpendicular to the direction of regional maximum tensile stress and the cross joints are perpendicular to the local maximum tensile stress (Bai et al., 2002)

Another common joint system consists of joint sets that intersect at 60/120 degrees and are associated with compression and shear fracturing. In folded rocks, strike-oriented joints are usually dominant along the crests and troughs of the fold and the limbs of the fold show mixtures of dip, strike, and 60-degree shear joint systems (Klimchouk and Ford, 2000). The planar breaks that result from faulting and fracturing serve as the principal structural channels for groundwater to flow in almost all karstified rocks (Klimchouk and Ford, 2000).

Karst

Aley et al. (1993) define karst as "a three dimensional terrane developed on and within a soluble bedrock". Dissolution of subsurface carbonates (such as limestone and dolomite) and evaporites (such as halite and gypsum) is often expressed on the surface where water is concentrated into subterranean conduits. This funneling of water yields specific surface landscapes with distinctive hydrology and landforms. Collectively termed "karst topography", these surface features include sinkholes, sinking streams, springs, blind valleys, and cave openings. The term "karst" however, is not limited to surface features, as often there are subterranean karst systems and karst aquifers with no surface expression (Klimchouk et al., 2000). Huntoon (1995) is quoted in Klimchouk and Ford (2000, p.45) and defines karst as:

> "The karst system is an integrated mass-transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organized to facilitate the circulation of fluid."

Carbonic acid (H_2CO_3) is chiefly responsible for the natural dissolution of carbonates to form caves (Moore and Sullivan, 1997). Carbonic acid is a weak acid that forms from the dissolution of carbon dioxide in water, and is mostly found in the soil and atmosphere (Palmer, 1991):

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \quad (\text{or } H^+ + HCO_3^-)$$

$$\text{Carbon dioxide + water} \rightleftarrows \text{Carbonic acid}$$

Carbonic acid percolates downward and comes in contact with limestone (calcite), which then dissolves into a calcium bicarbonate solution shown by the following open system reaction:

$$CaCO_3 + H_2CO_3 \rightleftarrows Ca^{2+} + 2HCO_3^-$$

$$\text{Calcite + Carbonic acid} \rightleftarrows \text{Calcium bicarbonate solution}$$

if no CO_2 is present (closed system), dissolution is much slower:

$$CaCO_3 + H_2O \rightleftarrows Ca^{2+} + CO_3^{2-} + H_2O$$

This double reaction results in the dissolution of limestone along joints, faults, and bedding planes creating conduits of water flow (Klimchouk et al., 2000). In karst areas, these conduits develop along the areas of greatest water movement (EPA, 2002). The most fundamental element of an evolving karst system is a single fracture, where calcite-aggressive water of constant hydraulic head flows from entry to exit. Varying conditions in lithologies, carbon dioxide input, and changing hydrological boundary conditions change the rate of dissolution and change the odds for these competing conduits (Dreybrodt and Gabrovsek, 2003).

Cave Patterns

Because cave patterns reflect the geologic structures that controlled the flow of the cave-forming groundwater, it is useful to understand the structural geology, geologic history, and geomorphic history of an area when creating karst models of specific areas (Palmer, 2000; Sasowsky, 1999). It is also useful to analyze the preferential paths of cave development because this gives insight to orientation and position of undiscovered caves, thus allowing for a more complete karst model

(Sasowsky, 1999). In order to understand the different cave patterns (cave morphology) that have been observed using previous karst models, it is important to first describe some factors that directly influence karst aquifers, thus allowing the different cave patterns to evolve. The influencing factors listed and described herein are not meant to be comprehensive of all of the factors that affect karst aquifers but will help the reader understand concepts and findings described later in this paper. These factors include recharge, and geologic influences of lithology, stratigraphy, and geologic structures.

Based on the different types of recharge and geologic influences, several models have been created in order to explain cave morphologies (Palmer, 2000). Each cave pattern is uniquely controlled by a hierarchy of hydrologic factors, mainly by the nature of groundwater recharge to the karst aquifer (Palmer, 1975, 2000). In fact, the location and overall trend of a cave depends on the recharge and discharge points within a karst aquifer. Several types of recharge for karst aquifers have been recognized, two of which are outlined below (White, 2003; Palmer, 2003a):

1. Allogenic recharge- Recharge derived from runoff of neighboring or overlying nonkarst rocks that drains into a karst aquifer through large fractures, sinkholes, and sinking streams.

2. Diffuse or dispersed infiltration- This occurs when precipitation onto the land surface infiltrates through the soil (or a porous but insoluble caprock such as sandstone) and may take days or weeks before migrating downward through the overlying rock or along fractures toward the water table.

Geologic influences of lithology and stratigraphy refer to bedrock characteristics that vary within each karst aquifer. The thickness of the rock strata, the general tendency of whether a rock unit is conducive to cave development (i.e. limestone versus dolomite), and whether confining or caprock units are present are all lithologic or stratigraphic factors that influence karst aquifers. A cave's morphology is also greatly influenced by the structural nature of the surrounding bedrock. The variability of geologic structures such as the degree of folding, presence of faults and fractures, and bedding plane orientation all indicate the general direction of an aquifer's flow, and thus determine the unique passage shape and trend (Sasowsky, 1999; Palmer, 2000). For instance, if active or recent faults are present, groundwater flow may be concentrated along the fault plane or cave development may become diverted or dammed. If the fault has been filled with secondary mineralization, the fault may have no effect on diversion water flow paths at all. The degree of folding influences karst aquifers because areas of strongly folded rock tend to have conduits oriented along strike (White, 2003). In areas of little folding, caves tend to show more highly integrated drainage patterns. The degree of folding, of course, influences the dip of the strata, thus affecting the direction of groundwater flow within the karst aquifer. In the unsaturated (vadose) zone, groundwater flow paths are likely to have a strong down-dip component because gravitational waters tend to follow the steepest paths, such as vertically or steeply dipping fractures (Figure 2). Because groundwater exhibits a down-dip component in the vadose zone, many vadose cave passages also demonstrate a strong down-dip component, particularly in well-bedded rocks (EPA, 2002; Palmer, 2003a). In the saturated (phreatic) zone, there is a strong tendency for flow paths to follow strike (EPA, 2002). Thus, phreatic cave passages do not show a consistent relationship to dip, unless that is the only path to an outlet (Palmer, 2003a). At the top of the saturated zone, often called the water table, the dip of the rocks loses its influence and gravitational forces are offset by increasing hydrostatic pressure. At this confluence, water follows fractures along strike which is the most efficient path to the nearest outlet (EPA, 2002). In general, the upstream portions of vadose cave passages form at the same time the downstream phreatic passages form (Palmer, 1991).

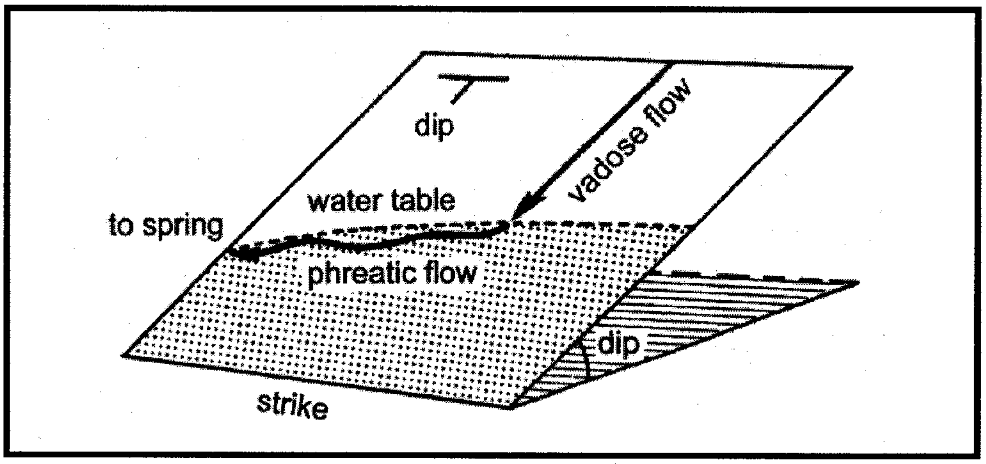


Figure 2. Diagram of idealized vadose water flow along inclined, bedded rocks. Vadose water flows down-dip along bedding planes. When water reaches the water table, the flow changes to a strike-oriented path which then follows the intersection of the water table and the dipping bed. (After EPA, 2002).

Based on the aforementioned hydrologic and geologic influences, Palmer (1991, 2000) suggested three basic cave geometry categories: 1) branchwork patterns (curvilinear and rectilinear/angular), 2) maze patterns, which consist of four types: network, anastomotic, ramiform, and spongework, and 3) rudimentary single passage (See Figures 3 and 4).

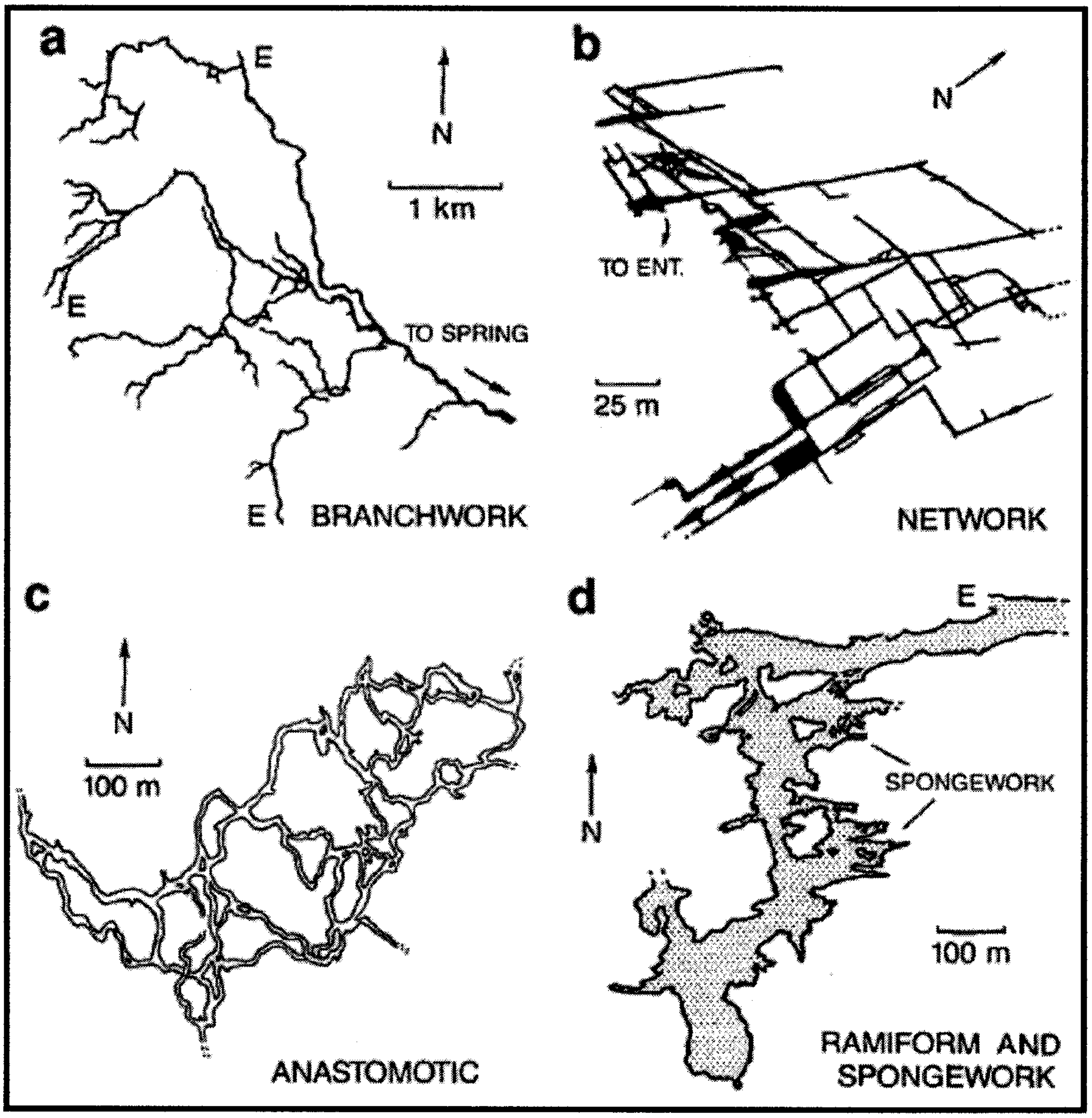


Figure 3. Examples of cave patterns.
A= Branchwork pattern (see also Rectilinear or Angular Branchwork pattern in Figure 4)
B, C, and D= Maze patterns. "E" denotes cave entrances. (After Palmer, 1991).

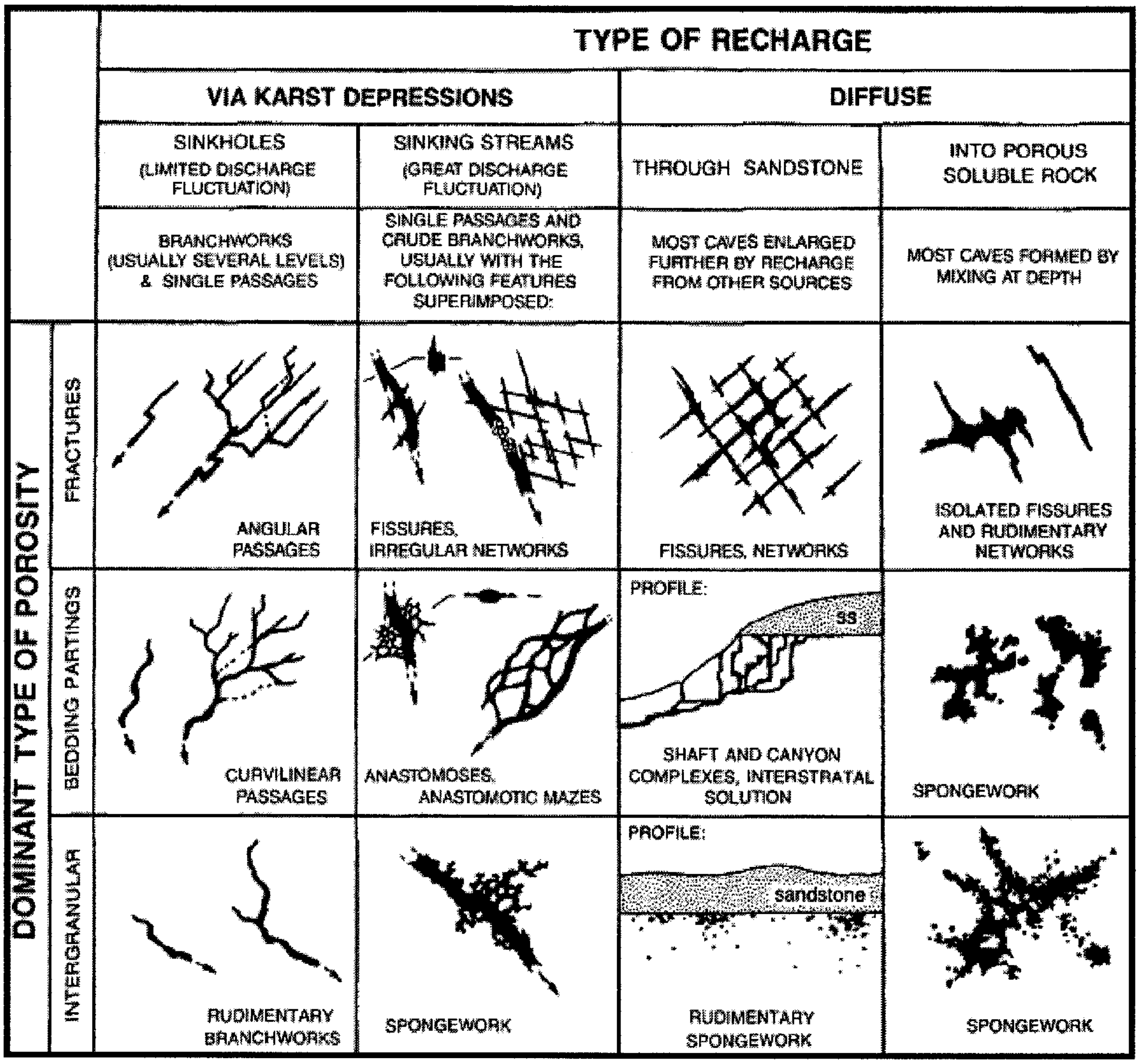


Figure 4. Cave patterns with associated types of recharge.
Maps are plan view unless noted. Hypogenic caves are not shown. (After Palmer, 1991).

The most common configuration, branchwork, consists of passages that join as tributaries in two basic patterns: curvilinear and rectilinear (angular) (Palmer, 1991, 2003). Curvilinear branchwork represents groundwater flow along bedding planes and rectilinear branchwork represents groundwater flow along fractures or joints. Both are influenced by recharge through depressions (sinkholes, sinking streams, etc.) with a limited catchment area in prominently bedded, low-dip strata (Palmer, 2000, 2003). Branchwork patterns dominate in most carbonate aquifers, in general because water initially forms subsurface first-order conduits, and then converges into higher-order conduits (usually of larger size) further down gradient (Dom and Wicks, 2003; Palmer, 1991).

Maze caves form only when growth rates are similar along many flow paths. There are several conditions that are favorable to the development of mazes and more specific conditions that form four specific types of mazes. Mazes are often formed when there is high-discharge flow during floods or when there is uniform recharge to all fissures. When water drains into all fissures simultaneously, passages are enlarged at approximately similar rates.

Four types of maze patterns have been identified: network, anastomotic, ramiform, and spongework. Network caves are the most common maze type (Palmer, 2003b). They are angular grids of intersecting passages formed by the widening of major fractures and favorable partings (Palmer, 1991). They commonly have closed loops- passages that circle back around to the same spot- which indicate that recharge is equally dispersed, giving competing passages an equal opportunity for enlargement. The uniform flow of water can come from above as dispersed infiltration or from below as artesian flow. Often the dispersed infiltration occurs through strata at low dip angles with an insoluble but porous caprock such as sandstone (Palmer, 2000). Maze networks can also be formed from direct channelization into jointed or fractured rock (often by flooding), by the mixing of thermal and meteoric water, or by the oxidation of rising hydrogen sulfide.

Anastomotic mazes are curvilinear tubes that are braided together, forming many closed loops (Palmer, 1991). They are produced by sources that have great discharge fluctuations and preferential groundwater flow is along bedding planes or low-angle fractures and faults (Dom and Wicks, 2003; Palmer, 2003b). Anastomotic caves are often associated with spongework caves and usually comprise only a portion of a cave.

Spongework mazes interconnect cavities of various sizes and resemble a three-dimensional pattern similar to that of a sponge. Sources of spongework type caves include <u>hypogenic</u> sources, floodwater, and diffuse recharge. They tend to form in highly porous or brecciated rocks where matrix porosity is the primary path for water to flow through (Palmer, 1991).

Ramiform cave patterns in plan view resemble ink blots with irregularly shaped rooms and offshoots extending outward in all directions. Ramiform caves are almost all hypogenic, including mixing of thermal and meteoric water or by the oxidation of rising hydrogen sulfide (Palmer, 1991, 2003b).

Rudimentary single-passage caves are rudimentary forms of any of the previous cave types and can form from any of the aforementioned processes (Palmer, 2000).

Weighted by length, Palmer (1991) observed the following breakdown of morphologies, which represent all of the known caves in the world longer than 3 km (~2 miles), within 1%: ~65% of caves are identified as branchwork, 17% as network, 10% as anastomotic, 8% as ramiform, <1% as spongework, and <1% a rudimentary single passage. Weighted by frequency, ~57% of caves worldwide are identified as branchwork, 17% as network, 14% as rudimentary single passage, 5% as spongework, 4% as ramiform, and 3% as anastomotic.

In addition to the aforementioned morphologies, Osborne (2003) introduced a different type of

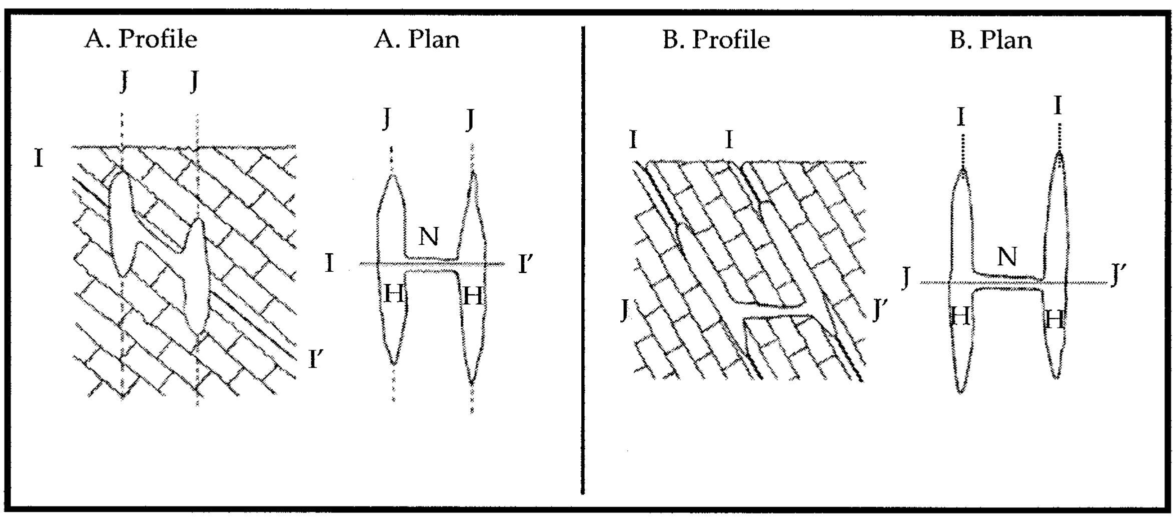


Figure 5. Halls and narrows.
Plan and Profile A exhibit moderately dipping limestone at approximately 40 degrees. Vertical joints, J, have developed parallel to strike and another set of joints have developed along I, the Inception Horizon. Halls, H, have developed along the joints parallel to strike and Narrows, N, have developed along the Inception Horizon parallel to bedding.
Plan and Profile B exhibit steeper dipping limestone at approximately 60 degrees. Halls have developed along Inception horizons parallel to bedding and narrows have developed along joints perpendicular to bedding. (After Osborne, 2003).

maze-type cave. Differing from maze network morphology outlined by Palmer which develop in gently dipping strata, these "halls and narrows" develop in steeply dipping strata (Figure 5). Structurally influenced, these caves develop elongated passages parallel to strike (halls) and narrower, shorter passages perpendicular to strike (narrows). With moderate dips, halls roughly follow joints that are perpendicular to bedding and narrows that are parallel to bedding. As dips become steeper (>30 degrees), just the opposite occurs: halls become more influenced by (and parallel to) bedding, while narrows follow joints roughly perpendicular to bedding.

STUDY AREA AND SIGNIFICANCE OF RESEARCH

Local Topography, Climate, and Geology

Nicknamed "Virginia's Little Switzerland", Highland County is aptly named due to the high, narrow mountain ridges, which average over 1,000 feet of relief (Parrott, 1948). These parallel, linear ridges are situated northeast-to-southwest with a regional strike of about N40°E and are separated by narrow river valleys. Elevations from the valley bottoms to the mountain knobs range from approximately 1,700 to 4,500 feet above sea level (CSPDC, 2007; USDA, 2004). Average annual minimum and maximum temperatures from 1971 to 2000 were 36.4 and 59.6

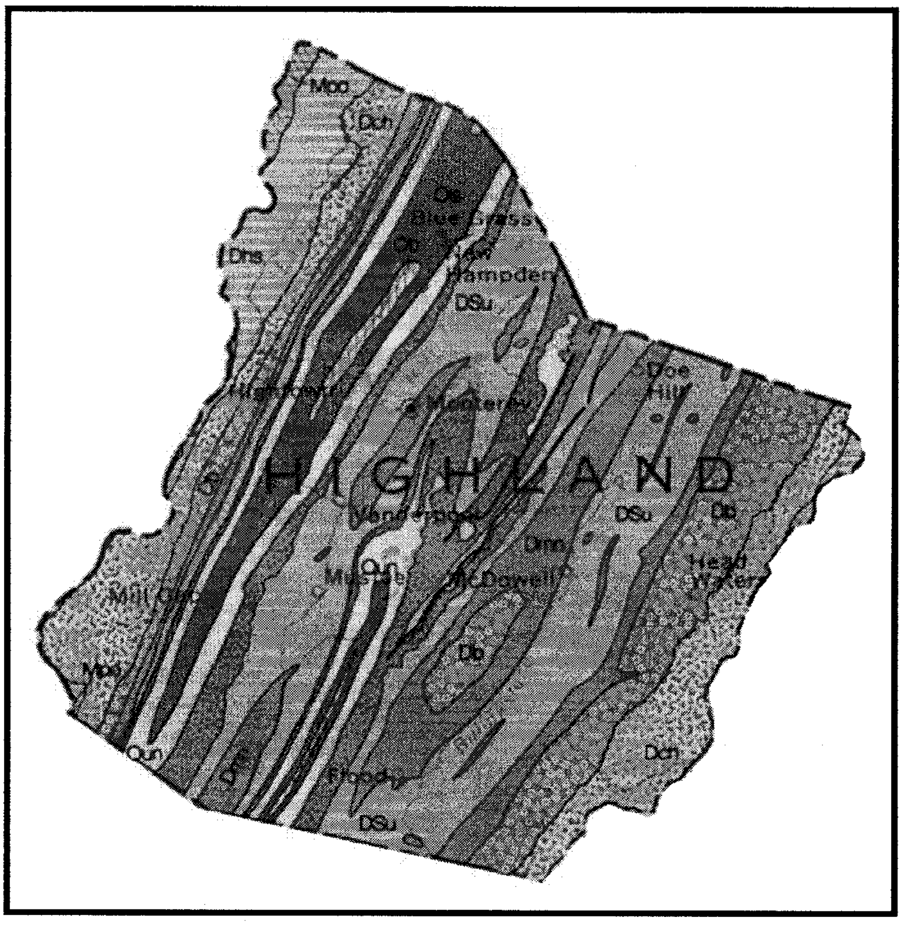


Figure 6. Generalized geologic map of Highland County, Virginia. Carbonate units include: Devonian and Silurian-age DSu (light gray); and Ordovician-age Ols (dark gray) and Ob (gray striped). (After Virginia Division of Mineral Resources, 1993 Geologic Map of Virginia).

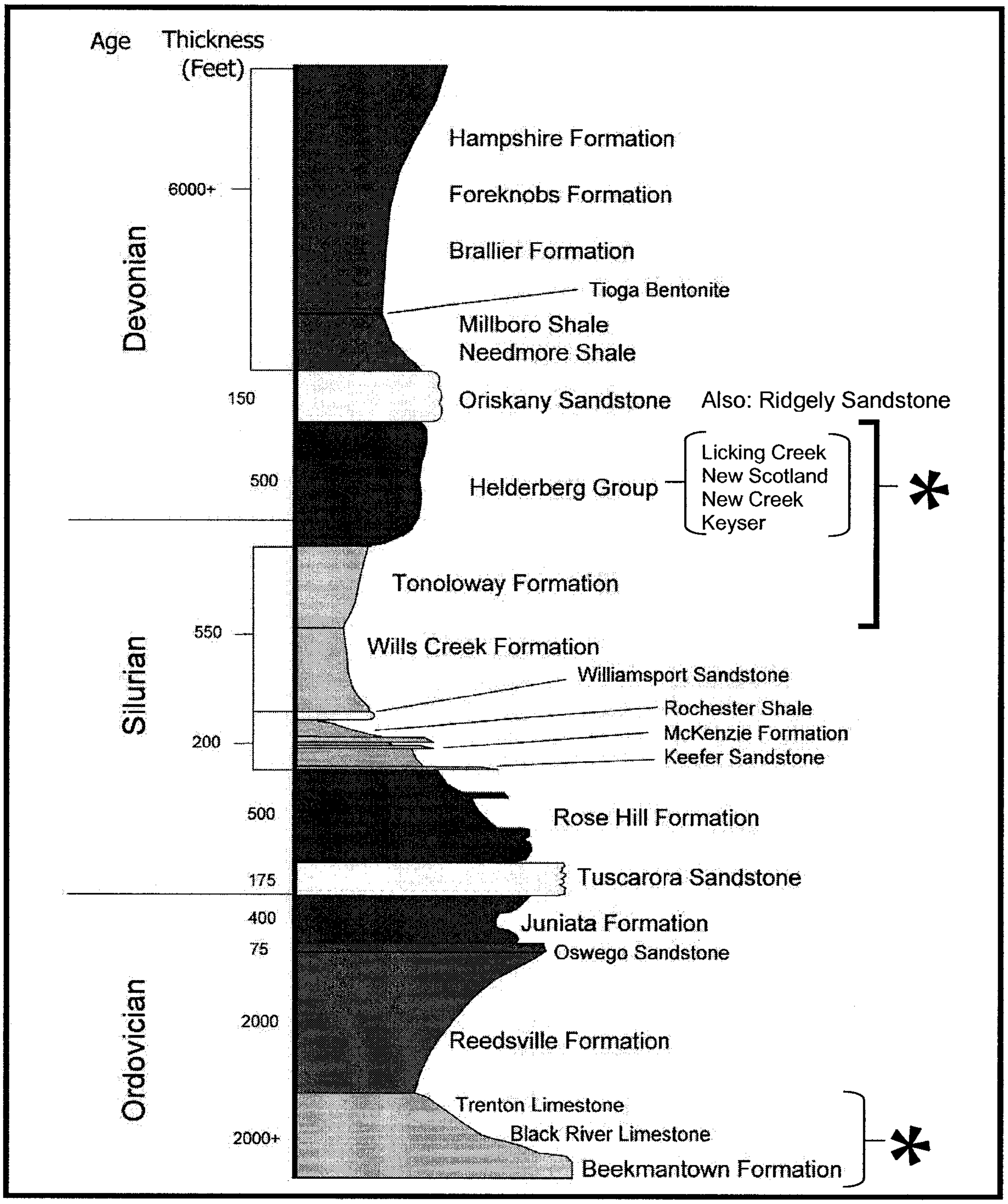


Figure 7. Stratigraphic column of Highland County.
The major limestone units conducive to cave development are denoted with an asterisk (*). (After Tso et al., 2004).

degrees Fahrenheit, respectively and the average annual total precipitation is 43.76 inches (SERCC, 2006). Outcrops of sedimentary strata (Figure 6) exist throughout the county and range from early Ordovician (Beekmantown Group) to early Mississippian (Pocono Formation) (Butts, 1973; Rader and Wilkes, 2001; Ryder, 1992). At least 35 Cenozoic igneous bodies, including Trimble Knob, an extinct volcanic neck, can also be observed throughout the county. The Paleozoic clastics and carbonates are complexly folded and faulted forming abundant large- and small-scale geologic structures including anticlines, synclines, thrust faults, chevron folds, kink folds, and overturned bedding (see Appendix B for Detailed Geologic Map, and Appendix C for Geologic Time Scale). Figure 7 illustrates the stratigraphic column from the Ordovician Beekmantown Formation through the Devonian Hampshire Formation. The Mississippian Pocono Formation (500-700 feet thick) unconformably lies above the Hampshire Formation (Butts, 1973). The main ridge-former in the area is the Silurian Tuscarora Sandstone (also called Tuscarora Quartzite or Clinch Formation), and creates the well-identified hog-backs and/or rocky outcrops on the ridges of Lantz Mountain, Back Creek Mountain, Monterey Mountain, Little Mountain, and Jack Mountain. Minor ridge formers, including the Keefer and Rose Hill Formations of the Clinton Group (Silurian), and the Ridgely (or Oriskany) Sandstone (Devonian) are found along the ridges of the Bullpasture Mountain (Bick, 1962). Figure 8 shows the large-scale mappable structures in the county from west to east, which include the Hightown Anticline (breached anticline), the Monterey Syncline, the Bolar Anticline, and the McClung Syncline (not shown). Numerous small-scale folds and faults also exist, creating very complex topography and geology. Figure 8 also illustrates the relationship between the two groups of cave-forming strata and their respective elevations. Profile lines are shown on both a topographic map and a generalized geologic map. Structurally speaking, the Ordovician beds lie near the center of tight anticlines and the Silurian-Devonian beds are exposed in open synclines, with the exception of the anticlinal Bullpasture Mountain.

The carbonates in Highland County are of Ordovician, Silurian, and Devonian age and result in approximately fifty percent of Highland's 416 square miles being karst terrain (VSS, 2004; Geospatial and Statistical Data Center, 2003). Caves are prominently found throughout the Ordovician and Devonian carbonate strata and appear to have minimal development in Silurian limestone. Figures 7 and 8 show the two main carbonate units conducive to cave and karst

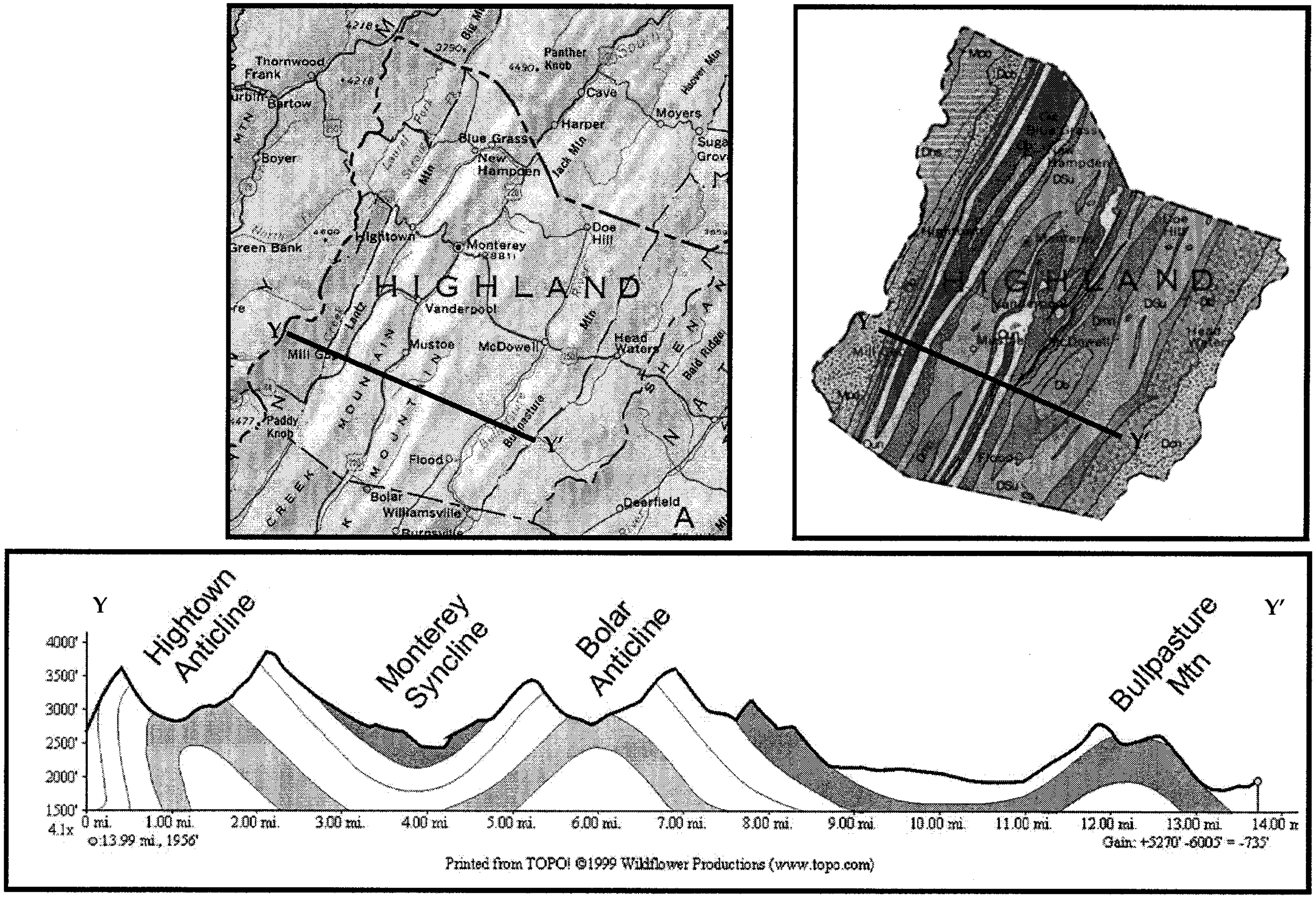


Figure 8. Generalized geologic cross section Y-Y′ showing relationship between Silurian-Devonian strata and Ordovician strata. Silurian-Devonian cave-forming strata is denoted as dark grey, Ordovician cave-forming strata as light grey. Bed thicknesses are representative. Vertical scale is approximately 3X.

development. These carbonate units and other Paleozoic carbonates are found throughout western and southwestern Virginia creating karst landscapes along Virginia's western border.

The older Ordovician limestones and dolostones are found in the breached anticlinal valleys along the western and middle portions of the county. These valleys are typified by sinkhole plains, rolling hills, and few, small surface streams. Although the literature indicates that the Ordovician limestones range from fine- to coarse-grained, the author observed the cave conducive-limestone to be micritic or at least very fine-grained and with few clastic impurities (i.e. sandy lenses). Although chert layers were described in the literature, very few examples were actually observed by the author in roadside outcrops. Where the chert was observed in caves, the layers did not appear to impede cave development. Bedding in the Ordovician limestone tends to be thick with overall limestone thickness of approximately 1000′ (305 m) from the top of the Beekmantown Formation to the top of the Edinburg Formation within the Trenton Group. When the dolomitic Beekmantown Formation is included in this thickness, carbonate thickness extends to over 3000′ (914 m) in Highland County. Observed fossils in the Ordovician carbonates included ostracods, crinoids, brachiopods, cephalopods, bryozoa (*Hallopora*) and trace fossils (*Chondrites*).

The Younger Silurian-Devonian carbonates dominate the landscape along the flanks of several forested mountains. The mountain flanks are characterized by hardwoods and are steep to very steep with sporadic sinkholes and intermittent surface rivulets. The Silurian-Devonian carbonates were observed to be extremely variable in nature, with matrix ranging from fine- to very coarse-grained and numerous impurities such as clastic sandy lenses. Silurian carbonates tended to be more shaly in nature. In the literature as well as in the field, it was often difficult to determine the lowermost Devonian strata from the uppermost Silurian strata. Bedding in Devonian and Silurian limestones range from laminated to thickly bedded. Fossils are abundant throughout and observed fauna include *rugosa, favosites, hallopora, fenestella,* crinoids, cephalopods, brachiopods, trilobites, and stromatolites.

Local Cave History

Caves in the area have had a very colorful and interesting history according to records from the Highland County Cave Survey. Local stories tell of mothers hiding their sons in caves and rock shelters during the Civil War to prevent them from being drafted by the Union and Confederate armies. Also during the Civil War, at least four caves were mined for saltpetre by the Confederates to make gunpowder and another cave was used to harbor their guns. Several unique collections of bones have been discovered in Highland caves, including human bones, a boar's tooth and tusk, and bones from a Pleistocene peccary and an extinct Dire Wolf (also Pleistocene). Evidence of an ancient bear wallow has also been identified in a cave and members of the HCCS were the first to report a live bear in a cave to the VSS. Discovered near the Bullpasture River, the bear had apparently climbed down a 15′ (5 m) entrance drop and was as surprised to see the cavers as they were to see the bear! Needless to say, the cavers immediately clambered out of the cave and returned the following month to see that the bear had left. Many Highland caves were observed to have spectacular marine fossil assemblages, including rugosa coral over three inches long, intact brachiopods, stromatolites, and crinoid bushes with their holdfasts attached. Native American arrowheads were found in a cave and dated to between 8,000 and 3,000 years before the present. It is speculated that Native Americans may have hunted bears in that particular cave for over 5,000 years. Other evidence of human habitation has been found in several other caves and include makeshift rock walls, stone tools, clay pots with backwards swastikas, evidence of moonshine manufacturing, and signatures dating to the 1800′s.

Annual social parties, including Halloween parties, were held in at least two caves in the early 1900′s. School trips were apparently led in a Hightown cave and church trips into a pit on the Bullpasture Mountain. Several other caves include signatures and quotes, such as the "U.S. is now at war" (Figure 9). While performing field work for this project, many landowners enlightened us by adding to the local cave stories. One cave owner revealed that a former landowner had hidden the family's silver and gold in a cave during the Civil War so that the Union army would not confiscate it. Another resident recalled children skipping school and spending the time in a cave in Hightown. Yet another landowner even mentioned that he planned to hide his valuables, guns, and his family in his cave if there was ever another war or local terrorist activity.

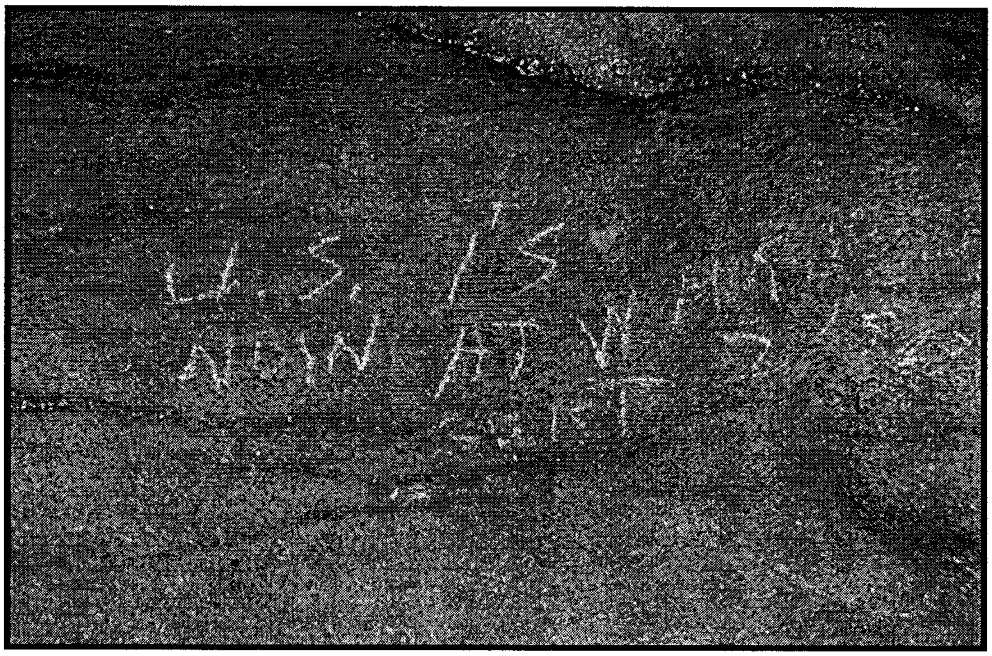


Figure 9. Photograph of historic cave graffiti.
The words "U.S. is now at war" written on cave wall. (From HCCS records).

Local Karst and Hazard Interaction

Karst is acknowledged as a non-renewable resource that can be particularly susceptible to disturbances, more so than many other land resources (Eakin and Beuhler, 2003). Karst landscapes are among the most highly exposed to contamination, especially where overlying soil is thin (EPA, 2002). In particular, groundwater is especially vulnerable in karst areas because surface water is channeled rapidly into sinkholes, sinking streams, or fissures and directly contributes to the local aquifer (Veni, 1999; Eakin and Beuhler, 2003). Without the advantage of soil filtering or microbial breakdown of contaminants, this direct input of contaminated water to the groundwater can cause serious water quality issues (VDEQ, 2006). In addition to groundwater contamination, karst areas are also susceptible to natural hazards including sinkhole subsidence, sinkhole flooding, soil instability, and groundwater sedimentation (Belo, 2003; Aley et al., 1993).

Karst and hydrology are often studied together because pollution potential in limestone regions is considered to be "high" and because both realms are so closely linked (VDEQ, 2006). In fact, karst studies are becoming quite prominent throughout the world, largely due to their unique relationship to water quality and their vulnerability to contamination as well as their natural hazards. With the advancement of computer mapping, remote sensing, and Geographic Information Systems (GIS), along with the scientific community's realization that karst areas are critically linked to water quality, cave information is becoming much more reliable and therefore, more useful. In order to fully understand a karst area, many types of karst and hydrologic models are often created to predict hazard impacts, contaminant migration, and local planning. States including Minnesota, Maryland, South Carolina and Kentucky have created karst models to predict sinkhole occurrence (ASCE, 2006) and West Virginia has compiled a statewide cave database of over 500 caves which has been used for conservation issues and land acquisition and protection for threatened and endangered species (Harrison, 2004). Several Virginia organizations have been implemented with the intention of documenting, conserving, and restoring Virginia karst waters (VDEQ, 2006). For planning purposes, the Virginia Department of Transportation (VDOT) has worked with the VSS to efficiently design roadways through high-impact karst areas and divert roads around caves that have been designated as "significant" (Waller, 2004). Increasing expenses for natural hazards (including sinkhole occurrence) have prompted government agencies to encourage state and local governments to prepare pre- and post-disaster hazard mitigation plans (Belo, 2003). Furthermore, in an effort to protect regional water supplies, agencies are also requiring studies of karst areas and their features (Veni, 1999). Because the Commonwealth of Virginia has mandated that localities prepare a water supply plan, karst terrains are being recognized as special areas of concern throughout Virginia (Figure 10) (CSPDC, 2007).

In order to develop resource management and data accessibility for planning purposes, several foreign countries have commenced building karst feature databases (ESRI, 2006). Unfortunately, few U.S. states and few western Virginia counties have adopted management plans for minimizing hazard risks in karst terrain. Therefore, a uniform method of accumulating karst information has not yet been adopted (Belo, 2003). The cave resource inventories that have been conducted have been of tremendous value and can be enhanced to include the entire range of karst resources. Aley et al. (1993) recommends that management of karst landscapes should involve four components: 1) inventory of karst features, 2) delineations of recharge areas, 3) vulnerability mapping, and 4) incorporation of numbers 1-3 into land planning and land management decisions. Eakin and Buehler (2003) further recommend that the information gathered should be provided in digital format. They indicate that the key karst features that should be identified include: springs, gaining and losing streams, caves, solutionally enlarged fractures and bedding planes, sinking stream basins, swallets, and sinkhole areas (Eakin and Buehler, 2003; Aley et al., 1993; Veni, 1999). Veni (1999) further indicates that airflow, cave fauna, lithology, morphology, sediment, structure, topography, and recharge and discharge should also be noted and recorded electronically, including a GIS.

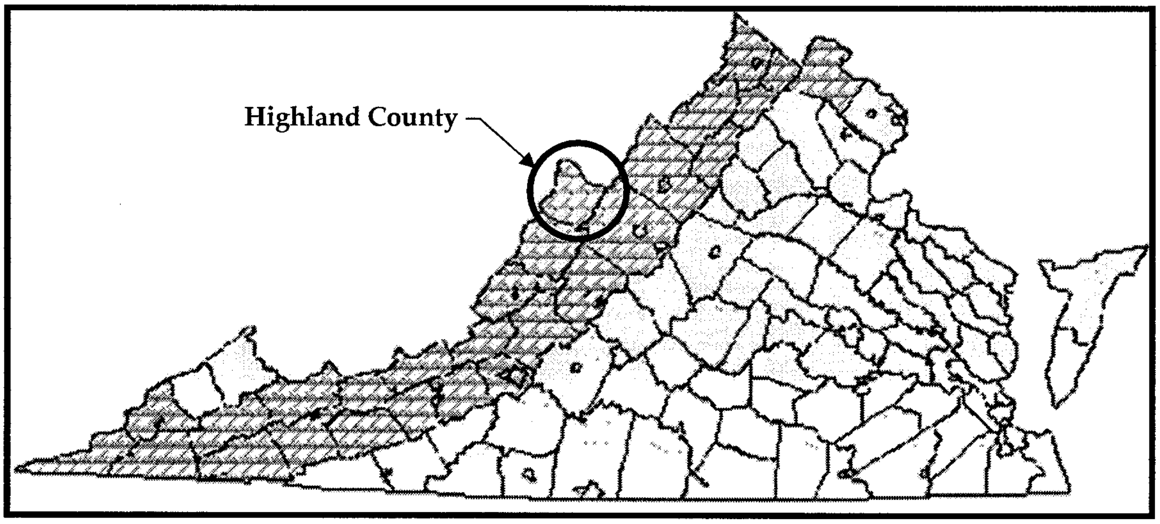


Figure 10. Map of Virginia counties exhibiting karst topography.
(After Virginia Department of Conservation and Recreation Natural Heritage Program, 2006).

Local Hydrology and Water Quality

Highland County is situated at the headwaters of two major drainage basins in Virginia- the northern portion of the county lies in the Potomac-Shenandoah watershed, while the southern portion lies in the [Upper] James River watershed (Figure 11). Both watersheds eventually flow to the Chesapeake Bay, the world's most productive estuary (VDCR, 2006). This setting helps illustrate the critical nature of Highland County's water quality as it affects the uppermost headwaters of not one, but two watersheds. The local cave systems and karst features are direct conduits for large area catchment basins that directly affect these watersheds.

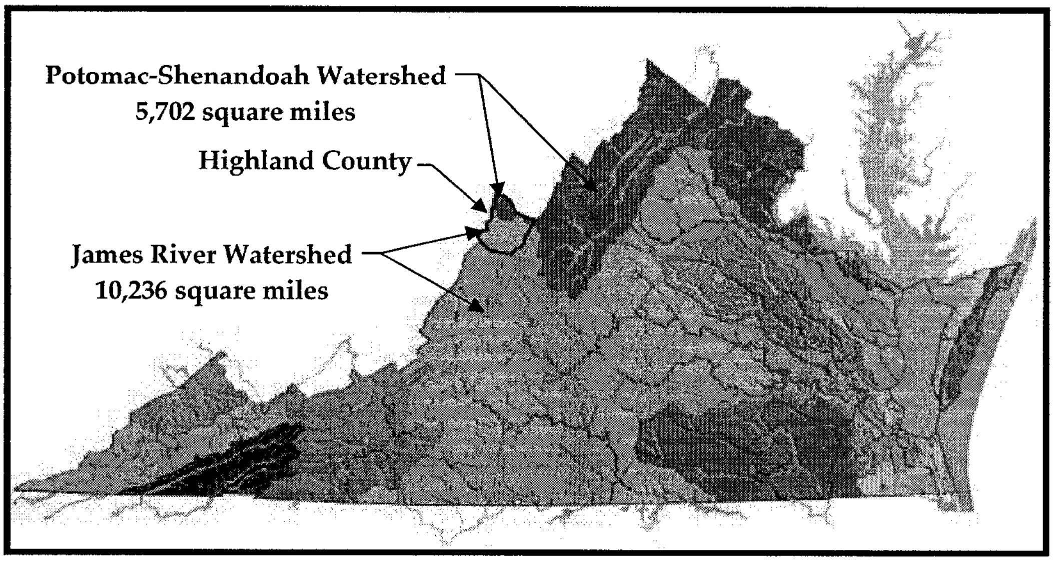


Figure 11. Watersheds of Virginia.
Highland County straddles a major watershed divide. (After Virginia Department of Conservation and Recreation, 2006).

Although the population of Highland County is sparse, the county is far from immune to contamination or pollution problems. In its Water Quality Integrated Report (2006), the Virginia Department of Environmental Quality (VDEQ) listed Straight Fork, Strait Creek, West Strait Creek, Bolar Run, Bullpasture River, and the South Fork of the South Branch of the Potomac River as having impaired waters (Table 1). The identified impairments include elevated water temperature, low pH, deficient results of benthic macroinvertebrate bioassessments, and violations of the *Escherichia coli* (*E-coli*) bacteria standard (VDEQ, 2006). The apparent sources of the impairments include natural causes, the sewage treatment plant in the town of Monterey, channelization, and non-point source agriculture (VDEQ, 2006). Thirty-four percent of Highland County's land area is considered to be agricultural, which may well account for the leading factor of water quality in Highland County (USDA, 1997 census). In fact, agricultural activities continue to be the most significant source of non-point source pollution throughout Virginia. The leading cause of the impairments in Highland County is the violation of bacteria standards, and agricultural practices appear to be one of the primary sources contributing to the bacteria standards violations. Leaking sanitary sewers, failing septic tanks and wild animals can also contribute to the bacteria standards violations (VDEQ, 2006).

In addition to these contaminant sources, at least 22 petroleum releases in Highland County have been reported to the Virginia Department of Environmental Quality since 1988. In all but three instances, a waterway was within 0.25 miles of the incident location (VDEQ GEMS, 2007). Furthermore, many of the releases were situated over limestone which may have provided a direct conduit to groundwater or nearby waterways via fissures or caves.

Table 1. List of Impaired Waters in Highland County.
(Compiled from Virginia Department of Environmental Quality, 2006)

Water Body	Impairment	Miles	Location	Source
Bolar Run	Water temperature	6.40	From headwaters downstream to confluence with Jackson River	Natural causes
Bullpasture River	*Escherichia coli*-Recreation	24.25	From headwaters downstream to confluence with Cowpasture River	NPS Wildlife other than waterfowl
South Branch of the Potomac River	*Escherichia coli*-Recreation	10.16	From headwaters downstream to VA/WV line	Non-Point Source (NPS)
Straight Fork	pH	7.04	From headwaters downstream to VA/WV line	Atmospheric deposition (acidity)
Strait Creek	*Escherichia coli*-Recreation Benthic Macroinvertebrate Bioassessments-Aquatic Life	3.24	From confluence with W. Strait Creek downstream to confluence with S. Branch Potomac River	Channelization
Strait Creek	*Escherichia coli*-Recreation	2.77	From headwaters downstream to confluence with W. Strait Creek	NPS
West Strait Creek	Benthic Macroinvertebrate Bioassessments-Aquatic Life	0.32	From Monterey STP downstream to confluence with unnamed tributary originating on Miracle Ridge	Municipal STP-Point source
West Strait Creek	Benthic Macroinvertebrate Bioassessments-Aquatic Life		From headwaters downstream to Monterey STP	NPS

Significance

Karst areas transport sediment differently from nonkarst areas because contaminants only need to move a short distance laterally before encountering conduits directly to groundwater. Contaminants in the local area include but are not limited to sediment, pesticides, petroleum products, salt from roads, refuse and dead livestock dumped in sinkholes, and bacteria from animal waste and faulty septic systems. Once contaminants reach conduits, there is no exposure to sunlight or filtration; therefore contamination is not retained within the system (Aley et al., 1993; Eakin and Buehler, 2003). Taking these problems into consideration, an understanding of the area's hydrogeology can help aid in reducing environmental impacts, improving clean-up response times, and preparing local hazard mitigation and water supply plans. The EPA (2002) indicates that if patterns of conduits are known, then patterns of surrounding flow can be predicted. Furthermore, Sasowski (1999) recommends that "any site investigation in limestone terrane include an evaluation of structural effects on the system".

Thus the greatest value of this study is to identify the local karst patterns, the controlling factors of cave development, and the role that geologic processes play in the speleogenesis of Highland's caves, which will aid in providing the groundwork for future hydrologic studies. This study is important, too, because members of the Highland County Cave Survey have been collecting cave data for over 15 years. This study collects, updates, and organizes a large amount of old and new karst information into a computerized and geo-referenced karst inventory which largely follows the model outlined by Veni (1999). Although not the main purpose of this study, this karst database was a significant undertaking and will continue to be updated and enhanced. Lastly, this study will provide insight to the HCCS, resource managers, and local landowners into potential cave-prone areas not yet discovered in Highland County.

GOALS AND OBJECTIVES

In an effort to provide the groundwork for future studies in the area, the main goal of this study was to gain an understanding of how geologic structures and processes control speleogenesis in Highland County, Virginia. In order to meet this goal, this study focused on the following objectives: 1) to characterize the morphology of caves in Highland County, 2) to determine if Highland County caves collectively were different morphologically than cave patterns worldwide, 3) to determine if Highland County caves formed in Silurian-Devonian strata were significantly different morphologically than those developed in Ordovician strata, and 4) to assess whether results of previous studies were accurate in predicting cave morphology and recharge patterns in Highland County, given the area's geologic structures and stratigraphy.

Based on worldwide observations presented by Palmer (1991 and 2003), it is hypothesized that the dominant cave pattern (by frequency and cave length) will be branchwork. Further, because of the lithologic differences in the Silurian-Devonian and Ordovician strata and the structural differences affecting each of these carbonate sections, it seems reasonable to conclude that obvious differences in cave development will be observed between the two areas. And finally, because of the strong folding in the area, one would expect the local caves to be mostly oriented along strike as White (2003) proposed, and perhaps reflecting a "halls and narrows" pattern as Osborne (2003) suggested.

METHODS

In order to meet the main goal of this study, which was to gain an understanding of the geologic processes controlling speleology in Highland County, large volumes of existing cave survey data were combined with new field observations into a computerized database for visualization and graphical and statistical analysis. Approximately 23 three- to four-day trips were made to Highland County for the collection of new cave and karst data. Out of 260 caves that have been surveyed and mapped by the HCCS, 191 caves were ultimately used in this study. Not included were sandstone caves, caves that could not be re-located due to incorrect historical coordinate entrance data, caves that had incomplete or non-existent electronic data, and caves that were inaccessible due to landowners or topographical restrictions (such as uncrossable rivers). Observations were taken and recorded at or around all cave entrances. Some caves were entered, however most caves were not due to time constraints.

In order to accomplish the study's objectives, existing data were organized and updated and a significant amount of new cave and karst data was collected. The data included, but was not limited to, historic cave reports and maps, cave owner information, historic cave entrance locations and elevations (updated with Global Positioning System (GPS) coordinates), cave survey statistics (including surveyed horizontal length, surveyed depth, surface length, and surface width), electronic cave passage information (including azimuth and inclination), and geologic information such as strike and dip, stratigraphy, and notable geologic structures.

Preparation

Prior to any field work, existing cave owner data was collected, organized, and updated in Microsoft Excel. A letter and liability disclaimer was composed and mailed to each cave owner explaining the project and asking for permission onto their property. Any landowners that did not respond via mail were contacted by telephone or in person at a later date. Ultimately, approximately 95% of the cave owners replied affirmatively.

Publications of the local stratigraphy, topography, and geology were obtained from state agencies in Virginia and West Virginia and included maps, open files, report of investigations, and working field maps. Other publications such as books, field trip guides, and theses also proved useful.

Existing electronic cave survey data and maps were also collected from the HCCS, VSS, and other local cave surveyors.

Field Methods

Several reconnaissance trips were initially made in order to gain an understanding of the geology and stratigraphy of the county. Published geologic maps, working field maps, report of investigations, measured sections, online geologic databases, lithologic descriptions, and field trip guides were all reviewed and emphasis was placed on deciphering the Silurian-Devonian and Ordovician strata, which are the main cave-bearing units in the county.

After receiving written and/or verbal permission from the cave owners, each cave entrance was re-located using HCCS records (which were merely dots on historic USGS topo maps). Ultimately, about 40% of the dots were significantly incorrect, so the entrance coordinate information was updated with a more contemporary method. This was done by obtaining a Universal Transverse Mercator coordinate, or UTM coordinate, using two handheld Garmin Etrex Vista GPS units. The datum used was North American Datum of 1927 for the Continental United States (or NAD 27 CONUS), consistent with USGS topographical maps. Coordinates were recorded from the unit that held the better accuracy. Coordinates of other karst features, such as sinkholes, springs, and sinking streams were also obtained and recorded for inclusion into a Highland County karst database. Maintenance of this database is ongoing by the Highland County Cave Survey and will continue after the course of this project.

Elevations of cave entrance were required in order to update existing karst database information and to use for the computer-generated modeling portion of this study and possible subsequent studies. Initially, two barometric altimeters were used to determine entrance elevations (Figure

12), but this method was overly time-consuming and the changes in relief (from known benchmarks to cave entrances), and sometimes in temperature, caused excessive variation in the altimeter readings. The subsequent method used elevations that were determined by the GPS receivers. Though the GPS-derived coordinates corresponded well to UTM points plotted on USGS 7.5 minute topo quads, the GPS-derived elevations did not correlate sufficiently, especially in areas of dense foliage. Therefore, cave entrance elevations were ultimately obtained by inputting the newly acquired coordinates into TOPO! software and interpolating the elevations (see Computer Methods).

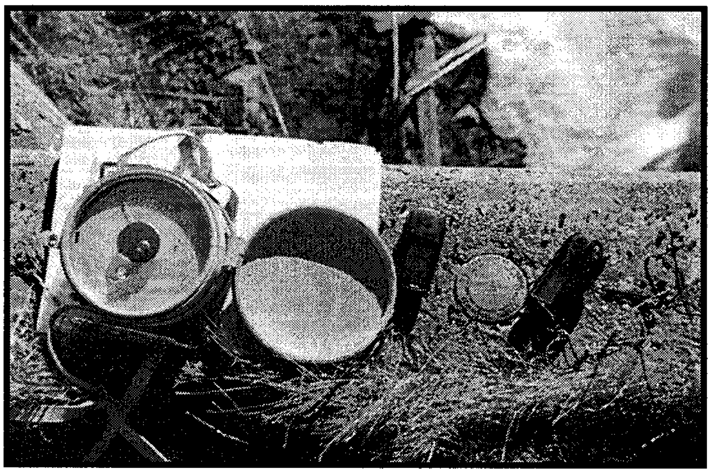


Figure 12. Field equipment.
One of two barometric altimeters, styrofoam insulation, and two handheld GPS receivers on a headwall with benchmark.

In addition to obtaining entrance coordinate data, bedrock samples were also retrieved and labeled and lithologies were described and recorded. If the stratigraphic formation was known, this too was recorded. Strike and dip measurements were taken and recorded at or near cave entrances where intact bedding was present, and any obvious contacts (such as a sandstone caprock) were observed and recorded. Digital photographs were taken of each entrance, and entrance types (such as sinkhole, fissure, bedding plane parting, etc.) were also recorded. Any geologic deformation at and around each cave entrance (including evidence of faults, folds, and fractures) was observed and recorded. And finally, any interesting observations, such as interesting stratigraphy, similarities to other caves, or items that could be input into the Highland karst database (e.g. springs) were also documented and recorded.

Computer Methods

All information that was gathered in the field and pertinent to this study was entered into a Microsoft Excel file (hereafter, the master file) for ease of sorting, graphing, and comparing. The karst database information was also updated but entered into a separate Highland County karst database Excel file. In addition to the field data, other information was updated and entered into the master file, including cave owner name and address, USGS topographic quad of the cave entrance, and cave statistics (such as total surveyed horizontal length, surveyed depth, surface length, and surface width).

Cave statistics for each cave were obtained using COMPASS Cave Survey Software by Fountain Computer, which is a cave mapping software. This information was used for morphological analyses and statistical comparisons. This process required input of all cave survey information, including station numbers, azimuth of foresights and backsights, inclination, and passage dimensions of all cave passages. Most of this electronic mapping information had been previously entered into individual COMPASS files; however, many had yet to be input or needed to be updated or finished. Once the electronic map data for each cave was complete, each file was individually opened and processed to reveal cave statistics and any errors. Errors were cross checked to their original survey field notes and any cave whose errors could not be resolved were removed from the study.

Rose diagrams (2–D) were also created in COMPASS for each cave and evaluated with its respective cave map to determine the cave's predominant direction of development (i.e. northeast-to-southwest along local strike direction, northwest-to-southeast along local dip direction, or other direction). The 2-D Rose diagrams were created with the petal width representing 10 degrees and the petal length representing total length of passages within that 10-degree increment. The 180-degree option (versus the 360-degree option) was used so that mapping direction did not weight the direction of the diagram's "petals". For example, when an east-west passage is surveyed, the compass angle can be recorded as 90 or 270 depending on whether the survey team is traveling east or west. For this reason, two types of Rose diagrams are offered by COMPASS: 360- and 180-degree versions. In the 360-degree version, passages are graphed based on the direction they were actually surveyed. This reveals a graph that is based on the direction that the surveyors proceeded rather than on the cave geology. In the 180-degree version, all angles greater than 180 are reversed so passages that are on the same fracture-line are grouped together. All cave statistics and predominant cave directions were ultimately recorded in the master Excel file for later analysis and graphing.

UTM coordinates for all cave entrances were input into a master TOPO! file to determine two-dimensional spatial relationships between all cave entrances. This analysis of cave location patterns provides cavers with an initial idea of future areas to search for new cave locations. TOPO! map software uses USGS 7.5 minute series topographic quads as the base map for its most detailed map. Once the entrance coordinates were input, entrance elevations were interpolated from the base maps and recorded in the master Excel file for later inclusion into COMPASS and Cave-X for 3-D modeling.

Also, areas of cave densities were observed in TOPO! and compared to geologic and topographic maps in order to theorize potential areas of undiscovered caves. Cave density observations may be somewhat misrepresentative because the areas of known caves are areas where the HCCS has had access to state- and privately-owned property. Despite this bias, areas where future search efforts need to be concentrated were apparent. These findings will not be identified in this paper due to a contract between the HCCS and the author, however, the information has been disclosed to the HCCS.

After interpolating the elevations in TOPO!, linework for each cave (azimuth and inclination data) was input into two COMPASS .mak files: one file for all caves in Ordovician limestone and another file for all caves in Silurian-Devonian limestone. Each cave was "attached" to its respective file by its entrance coordinate and elevation, therefore, the caves are spatially correct in three dimensions to one another. These two overall cave files were then opened in COMPASS and 2-D Rose diagrams were generated to determine the overall predominance of cave direction in both the Silurian-Devonian and Ordovician strata. The files were then opened in Cave-X, a

3-D interactive cave viewer, and 3-D Rose diagrams were generated in order to view cave formation at depth.

Individual cave linework (azimuth and inclination data) was also input into a GIS using ArcView by its respective UTM and elevation. In the end, GIS was not utilized for this project, but due to this effort, Highland County is currently the only Virginia county with all of its cave survey linework input into a GIS. This resource will ultimately provide a basis for future studies in Highland County, as well as a GIS-based karst database.

Analytical Methods

In order to characterize the overall cave morphology of Highland County caves and to determine if these patterns reflected worldwide cave patterns, individual cave maps and COMPASS files were examined visually and each cave was categorized based on its predominant cave pattern. The categories were based largely on Palmer's classification system of morphology (1991) which identified curvilinear and angular (rectilinear) branchwork, maze network, anastomotic, and ramiform/spongework patterns. Although Palmer (2003a) indicates that "branchwork patterns dominate in most carbonate aquifers," his 1991 models only compared cave patterns to worldwide caves longer than 3 km (~2 miles). The HCCS documents many smaller caves and only two known caves in the county are longer than 3 km- so "pits" and "rooms" were added as cave types. Additionally, the single passages that Palmer described and the fissures that Stafford et al. (2005) described both resembled characteristics of Highland caves. As a result, "single passage" caves described by Palmer were re-classified and absorbed into the categories "fissures" or "slot fissures." Stafford et al. (2005) defined fissure caves as being linear and descending at moderate slopes. The author modified Stafford's definition of a fissure to include narrow, linear passages less than 10 feet in height that narrowed at the terminus and perhaps included thinner, perpendicular passages that quickly terminated (Appendix D). Slot fissures were regarded as similar to fissures but differentiated by being more canyon-like with passage heights of at least ten feet high or more (Appendix E). With very few exceptions, fissures and slot fissures were primarily single passage caves.

Using Palmer's models and the added or modified categories, a more complete analysis of cave type in Highland County was determined and then compared to the worldwide classification of cave types. Caves that exhibited more than one dominant morphology were classified into more than one predominant category instead of just one. The distribution of cave patterns (by frequency and total surveyed length) in Highland was then computed and compared to Palmer's (1991) findings to determine if the predominant cave type in Highland mimicked the leading world distribution pattern (branchwork) based on both frequency and cave length. An interesting trend was observed regarding cave type and cave length, so an analysis of cave type to cave lengths was also performed by determining how many particular cave types were represented for specific cave length intervals.

In addition to analyzing cave patterns, caves were also categorized based on active vadose or phreatic conditions by reviewing cave maps or having first-hand knowledge of the character of the cave. Caves were determined to be phreatic if they contained perennial streams that ended in a sump (a section of flooded passage) or an exurgence to a base level stream or river. Because sumps can be vadose or phreatic, consideration of elevations and cave morphology were also

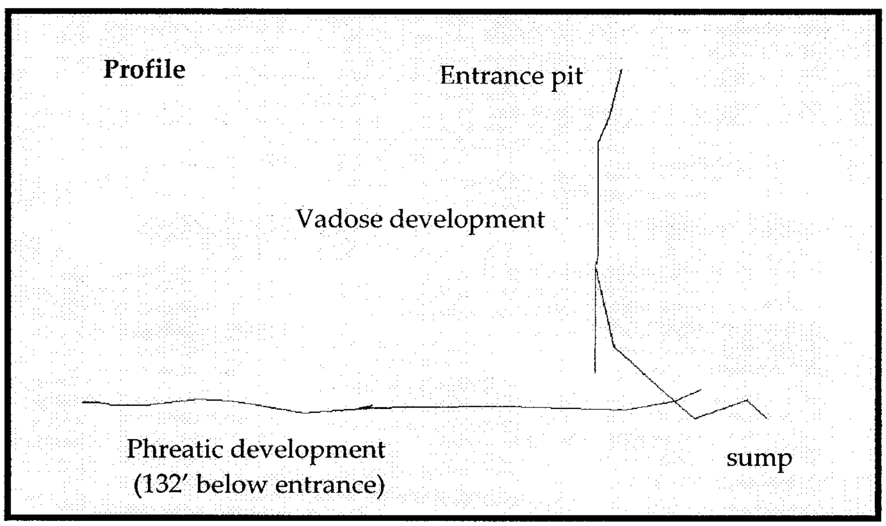


Figure 13. COMPASS linework of a Highland County cave in profile. Profile of Highland County cave showing vertical vadose cave development and horizontal phreatic cave development. The horizontal line is a perennial stream with several standing pools of water. Flow is to the right, ending in a sump at an elevation equivalent to the water table in this location.

taken into consideration. For example, cave profiles were observed in COMPASS as well as individual cave maps to determine if vertical cave passages were present, such as pits (vadose shafts) or canyons, which are characteristic of vadose development. Figure 13 shows a cave that was considered to contain both active vadose and phreatic characteristics.

For the purpose of determining if Highland County caves formed in Silurian-Devonian strata were morphologically different than those developed in Ordovician strata, several factors were compared. Similar to Stafford et al. (2005), the author used 2-D Rose diagrams to observe correlations with passage orientation and evaluated cave maps and linework in COMPASS to study orientation of the caves. First, a 2-D Rose diagram was created in COMPASS for all caves in the Silurian-Devonian strata and compared to the Rose diagram created of all caves in Ordovician strata. This was done to observe any similarities of overall cave development (by surveyed length) between the strata. The same comparison was then done in 3-D Rose diagrams to determine any similarities of cave development at depth.

In order to reduce bias created by long caves, the author created a method to analyze the frequency of caves oriented in particular directions. Predominant passage direction for each cave was established by visually evaluating Rose diagrams and cave maps for each cave and placing the cave into one of eleven categories. Figure 14 denotes the Rose diagrams of caves with strong predominant directions. Four of these directions (identified as categories 1 through 4) denote strong directionality in north, east, northeast, or northwest, respectively. Equally predominant cave formation along strike and dip (northwest and northeast directions) is denoted by category 5. If there was no predominant direction, the category 6 was assigned to the cave. Because there were numerous caves that showed a weak predominance in a particular direction, rather than a strong predominance, categories 1w through 5w (Figure 15) were also added.

In order to assess whether results of previous studies were accurate in predicting cave morphology and recharge patterns in Highland County, individual cave patterns and directions were analyzed by comparing cave maps, COMPASS line plots, and predominant cave direction to the nearest measurements of strike and dip that were gathered in the field and/or portrayed on the geologic maps. Then, using Osborne's (2003) description of halls and narrows and the predictions of vadose and phreatic cave development as mentioned previously, Highland's caves were again categorized based on these characteristics to determine whether they seemed to fit those proposed predictions.

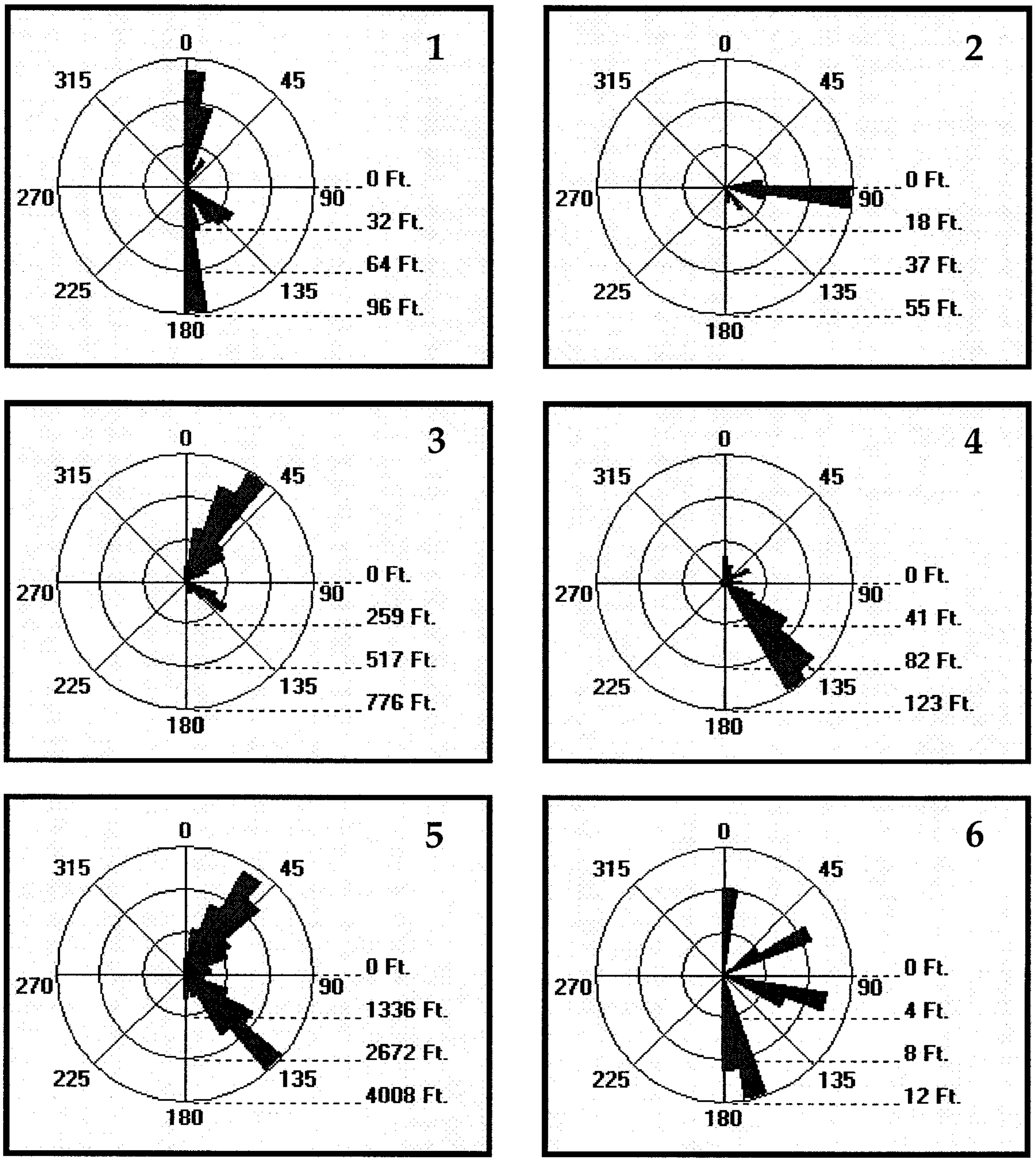


Figure 14. Rose diagrams showing examples of strong predominant cave directions. 1= N-S direction 2= E-W direction 3= NE-SW direction 4= NW-SE direction 5= NE-SW and NW-SE direction 6= No predominant cave direction.

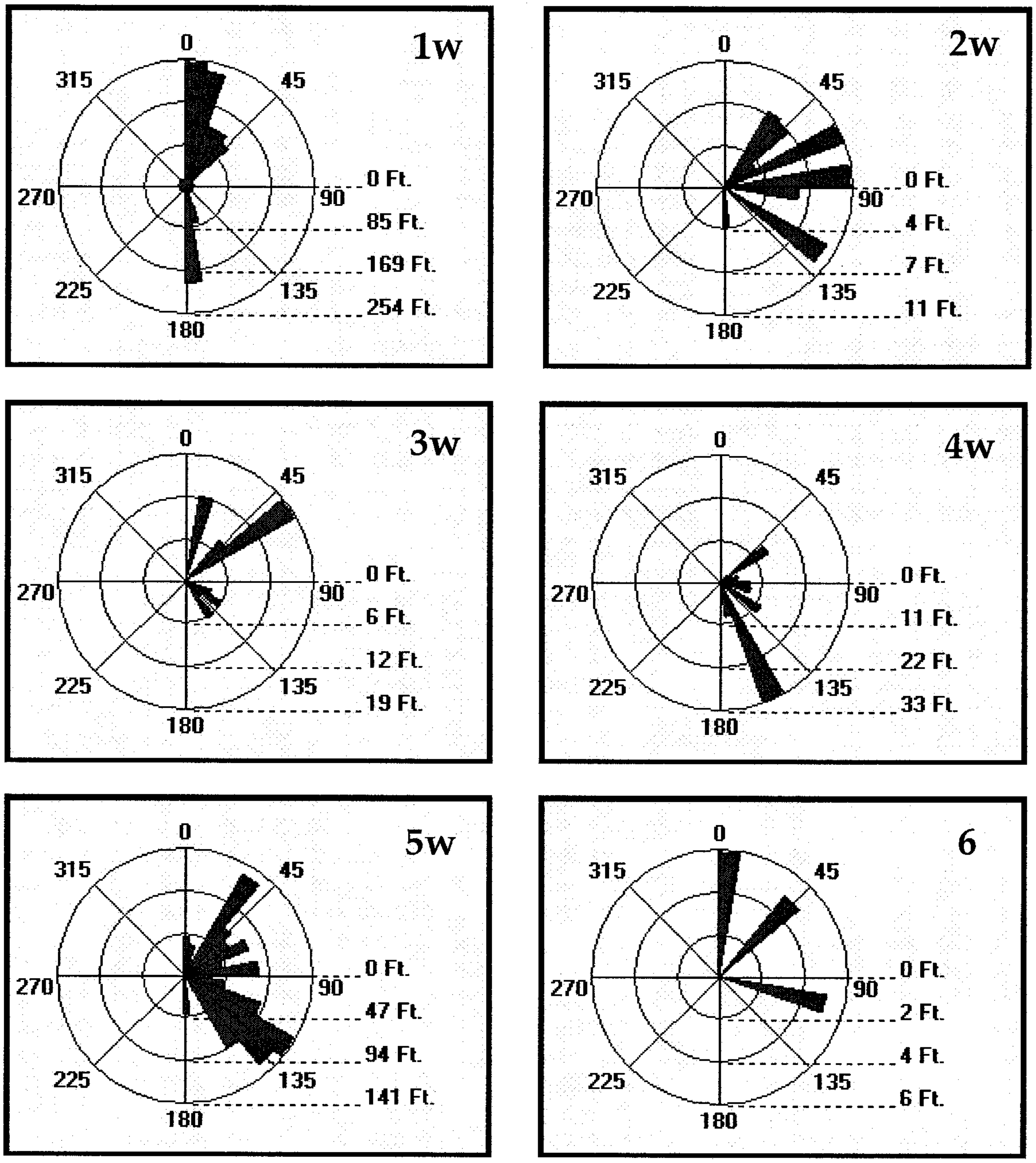


Figure 15. Rose diagrams showing examples of weak predominant cave directions. 1w= N-S direction 2w= E-W direction 3w= NE-SW direction 4w= NW-SE direction 5w= NE-SW and NW-SE direction 6= No predominant cave direction.

RESULTS AND DISCUSSION

In order to gain an understanding of how geologic structures and processes control speleogenesis in Highland County, Virginia, several ideas were incorporated for analyses. First, all 191 caves used in this study were categorized based on their cave morphology. Cave patterns introduced by Palmer (1991) and defined in Stafford et al. (2005) as well as patterns added/modified by the author were used as the basis for the classification. The predominant cave type in the county by frequency and cave length was then compared to the dominant cave pattern that is seen worldwide by frequency as well as cave length (branchwork). Prominent directions of cave passages were then observed by creating Rose diagrams and frequency charts of passage directions. Information was further analyzed by splitting the data into two groups: caves found in the Silurian-Devonian strata and caves found in Ordovician strata. The aforementioned comparisons were then made for the Silurian-Devonian and Ordovician cave groups to see if any striking similarities or differences could be determined.

And finally, given the area's geologic structures and stratigraphy in addition to results from the aforementioned analyses and additional observations, Highland's caves were compared to results of previous studies to determine if their predictions of cave morphology and recharge were reflected in Highland.

Results were both expected and surprising. Based on worldwide observations presented by Palmer (1991, 2003), it was hypothesized that the dominant cave pattern (by frequency and cave length) would be branchwork. Instead, cave morphologies in Highland were fissure-type caves by frequency and maze networks by length. Further, because of the lithologic differences in the Silurian-Devonian and Ordovician strata and the structural differences affecting each of these carbonate sections, it was reasonable to conclude that obvious differences in cave development would be observed between the two areas. In actuality, not many differences were observed between the strata. And finally, because of the strong folding in the area, the local caves were expected to be mostly oriented along strike as White (2003) proposed, and perhaps reflecting a "halls and narrows" pattern as Osborne (2003) suggested. Approximately one-third of cave passages *were* oriented parallel to strike, however approximately 27% (almost one-third) of the caves showed development along 60/120 degree intersections. Additionally, several caves could be considered "halls and narrows" as Osborne (2003) suggested, but approximately 50% of these caves were oriented such that the *narrows* were parallel to strike and the halls were parallel to dip (rather than the halls being parallel to strike).

Countywide Cave Patterns

All 191 caves were individually categorized by their predominant cave morphology based on Palmer's (1991) scheme of branchwork, maze network, anastomotic, ramiform/ spongework, and single passage as well as the "fissure pattern" concepts in Stafford et al. (2005; Figures 3 and 4). In several instances, more than one predominant cave morphology was observed, so some caves were classified into two or more cave types rather than one predominant type. Furthermore, the cave morphologies that Palmer introduced had to be expanded upon to include pits and rooms as well as modifying the "single passage" category (see Analytical Methods). These modifications were made because several caves were predominantly pits and rooms, and thus did not fit into Palmer's classification system.

Table 2. Comparison of cave types in Highland County to worldwide patterns based on frequency and total surveyed length.

Cave Type	Predominant cave patterns in Highland County (by frequency)	Cave patterns reflected worldwide (by frequency) (Palmer, 1991)	Predominant cave patterns in Highland County (by length)	Cave patterns reflected worldwide (by length) (Palmer, 1991)
Slot Fissure	**35.1%**	n/a	9.9%	n/a
Fissure	30.4%	14% (single passage)	2.8%	<1%
Pits	22.0%	n/a	n/a	n/a
Branchwork	16.8%	**57%**	38.9%	**65%**
Rooms	12.0%	n/a	n/a	n/a
Maze Network	7.3%	17%	**50.5%**	17%
Spongework	0%	5%	0%	<1%
Ramiform	0%	4%	0%	8%
Anastomotic	0%	3%	0%	10%
Total # Caves used in study	**191 caves**	**>500 caves**	**191 caves**	**>500 caves**

Data in Figure 16 and Table 2 illustrate the differences between caves worldwide (Palmer, 1991) and in Highland County based on frequency. More than 65% of Highland's known caves were solely or predominantly "slot fissures" (35%) or "fissures" (30%). Pits were the next most predominant cave pattern accounting for 22% of the county's cave types and curvilinear and rectilinear branchwork patterns comprised only 17% of Highland's caves. Rooms accounted for 12% of Highland's caves and maze network caves comprised 7% by frequency. There were no caves with predominant ramiform, spongework, or anastomotic patterns. Note that these percentages add up to more than 100% because several caves equally fit into more than one predominant cave type. Also shown are Palmer's (1991) findings of caves worldwide (longer than 3 km) being categorized as 57% branchwork, 17% maze network, 14% fissures, 5% spongework, 4% ramiform, and 3% anastomotic. These data indicate that Highland's cave

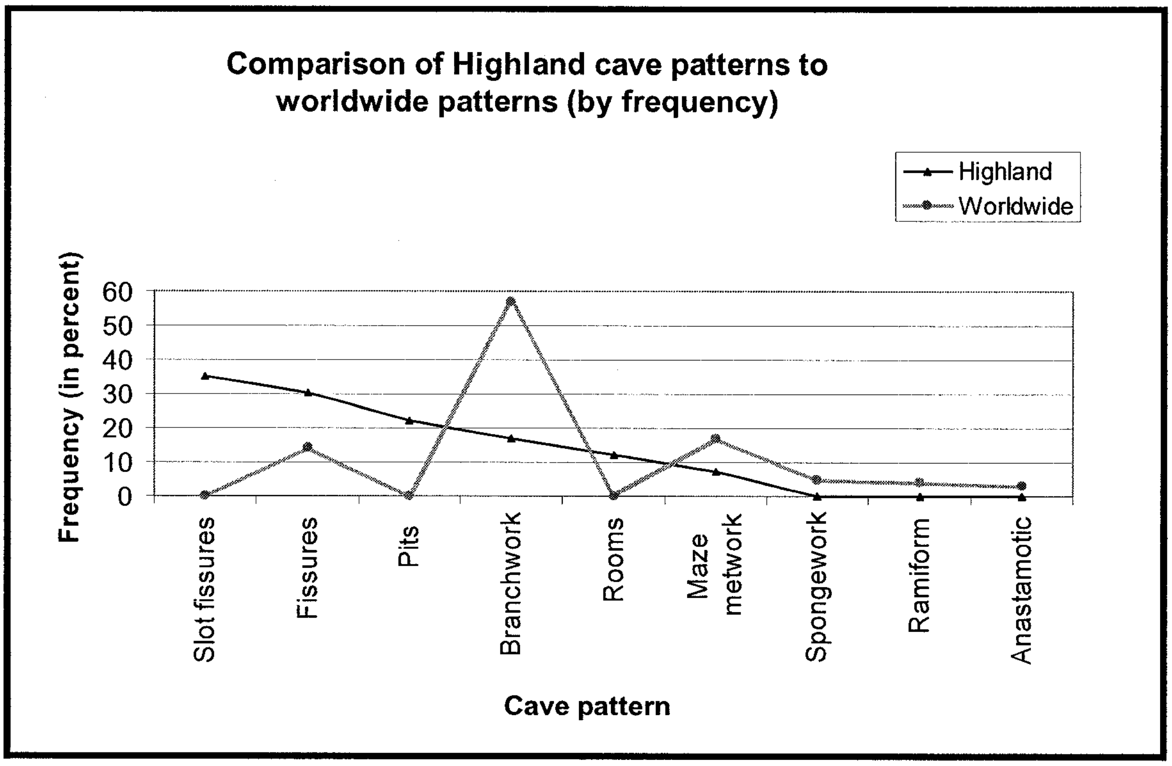


Figure 16. Comparison of Highland cave patterns to worldwide patterns by frequency. Highland's predominant cave types by frequency are fissures and slot fissures, followed by pits, branchwork, rooms, and maze network patterns, respectively. This frequency of cave type does not mimic worldwide findings (Palmer, 1991) which show branchwork, then maze network as predominant cave types. Worldwide frequency information on pits and rooms was not provided in Palmer (1991).

morphologies do not mimic worldwide cave patterns based on frequency.

Figure 17 compares Highland County caves with Palmer's (1991) survey, and shows that based on total surveyed length, maze networks were the predominant cave type in Highland County, at 50%. Branchwork caves (curvilinear and rectilinear) followed, making up approximately 40%, slot fissures constituted approximately 10%, and fissures comprised approximately 3%. There were no caves showing a predominance of ramiform, spongework, or anastomotic patterns. These percentages total slightly more than 100% because several caves fit into two equally predominant patterns rather than just one. Also note that these percentages are based on the total surveyed passage and are not based on individual lengths of predominant passage types alone. For instance, if 100' of a cave is considered branchwork passage and 400' is considered maze network, the total 500' of horizontal passage is included in the predominant category of maze network. This breakdown of cave morphologies still does not mirror Palmer's (1991)

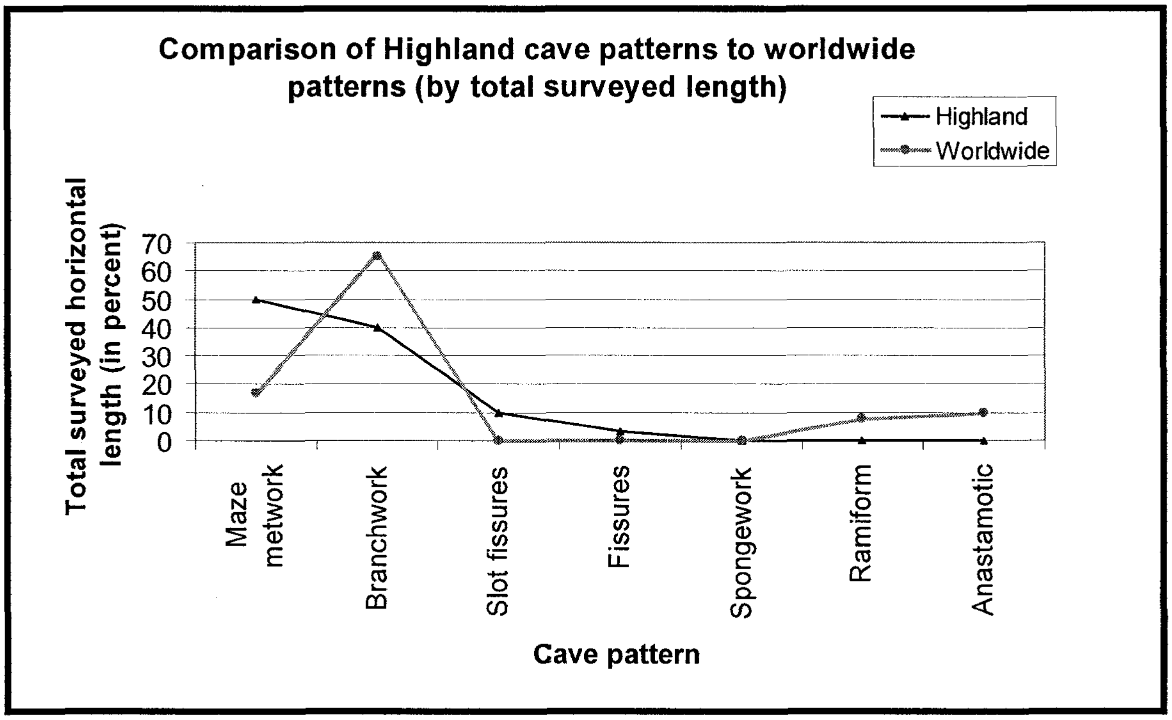


Figure 17. Comparison of Highland cave patterns to worldwide patterns by surveyed length. Highland's predominant cave types by total surveyed length are maze network, branchwork and then fissure-type caves. This frequency of cave types by total length does not mimic worldwide findings (Palmer, 1991) which show branchwork then maze network as predominant cave types.

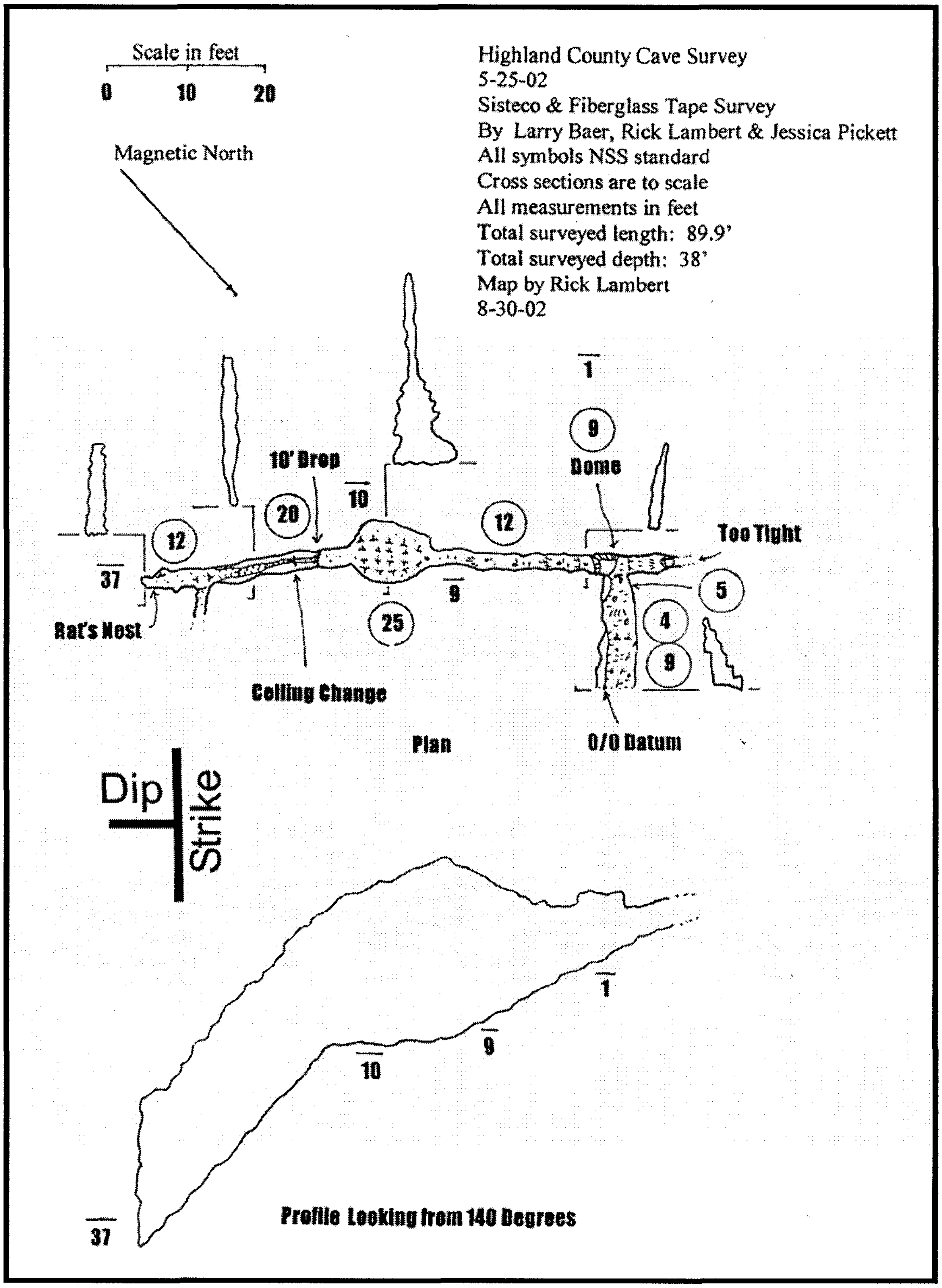


Figure 18. Example of a Highland cave showing halls forming parallel to dip and narrows forming perpendicular to strike.
Hall is shown parallel to strike and in profile. Narrows are formed parallel to strike. Cave location and name not identified due to author's agreement with VSS and HCCS. (After map from Highland County Cave Survey files).

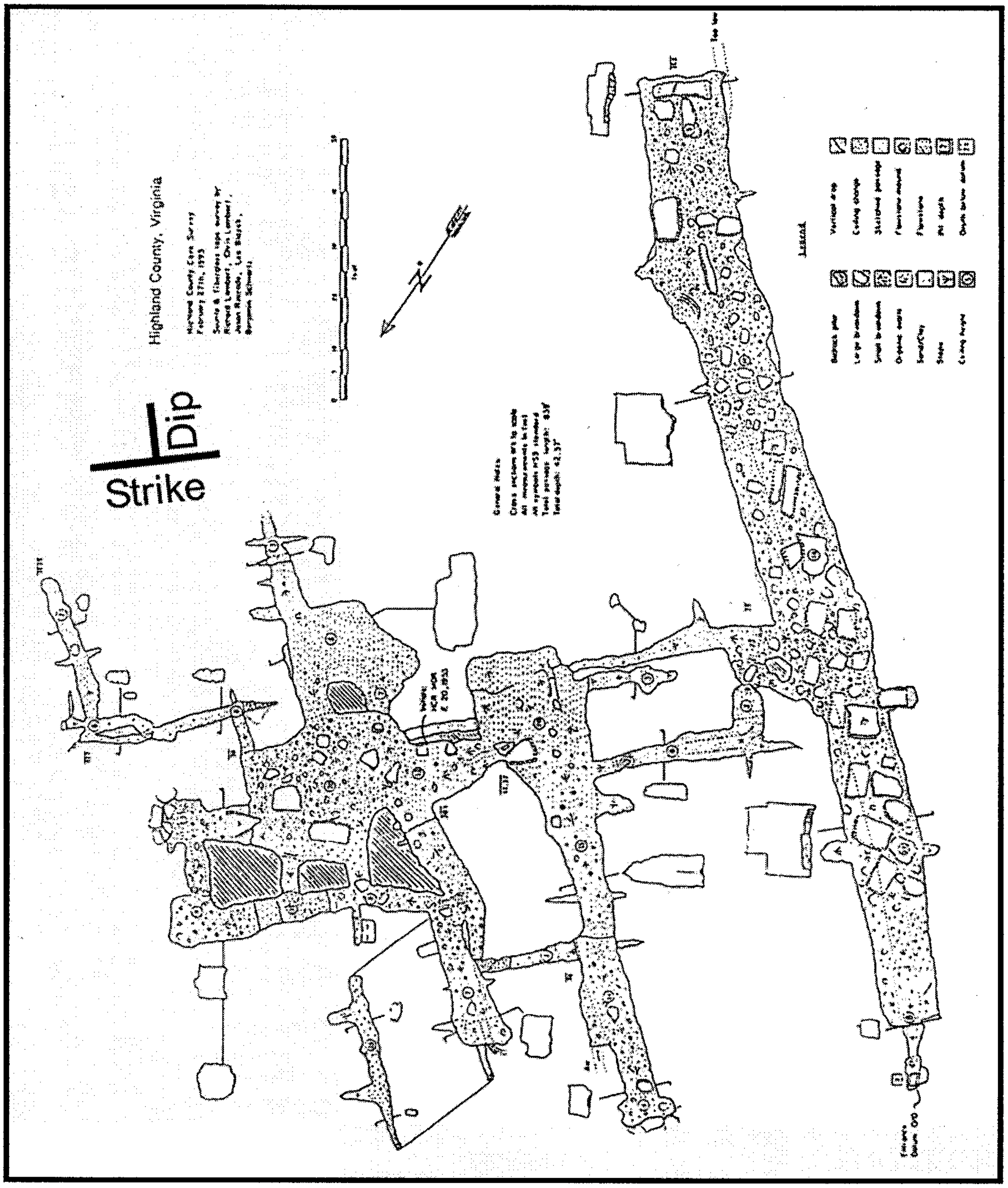


Figure 19. Maze network cave exhibiting halls parallel to dip and narrows parallel to strike. Cave location and name not identified due to author's agreement with VSS and HCCS. (After map from Highland County Cave Survey files).

worldwide findings by length of 65% branchwork, 17% maze network, 10% anastomotic, 8% ramiform, and <1% for both spongework and fissures.

Of the Highland County caves that could be possibly classified as halls and narrows as outlined by Osborne (2003) in Figure 5, approximately 50% of these reflected orientations similar to Osborne in that the halls were parallel to strike. Rock surrounding these caves had dip angles ranging from 7 to 71 degrees with approximately 50% showing dip angles over 30 degrees (where a dip angle could actually be determined). However, approximately 50% of these caves, were actually oriented such that the *narrows* were parallel to strike and the halls were parallel to dip (rather than the halls being parallel to strike). Figures 18 and 19 show examples where the halls have formed parallel to dip and the narrows have formed parallel to strike. Rock surrounding these types of caves all showed dip angles less than 30 degrees (where dip angles could be determined). Approximately 98% of Highland's caves showed passages to be completely vertical in cross section as in Figure 5, Profile A (Osborne, 2003). Very few exhibited patterns reflected in Figure 5, Profile B where the passages developed parallel to bedding. Instead, the passages were affected by bedding in that the halls actually stairstepped down-dip along bedding (perpendicular to strike) rather than forming along the bedding parallel to strike (profile, Figure 18).

Countywide Cave Patterns Related to Cave Lengths

In the absence of worldwide figures on cave lengths for comparison, Virginia's statistics were used to compare cave lengths (Lucas, 2007). Only 39% of Highland's caves contain over 100′ (30 m) of surveyed passage, while 51% of all Virginia caves are longer than 100′ (30 m; Figure 20). However, Highland's 12% of caves over 500′ (152 m) of passage are similar to the state's findings of 18%. Approximately 2% of Highland's caves are over 5,280′ (1,609 m), which matches Virginia's percentage of caves over one mile of passage. Even though the number of Highland's caves that are over 100′ (30 m) in length are fewer than that found in the state, the overall trend between the two are almost identical. Both even show a similar change in trend at caves lengths over 500′ (152 m).

When cave lengths in Highland were broken down into smaller increments, certain cave types appeared to be associated with specific lengths (Table 3). Data show that the total surveyed passage length of fissure caves range from 5′ to 257′ (1-78 m) of passage, with only 12% of them

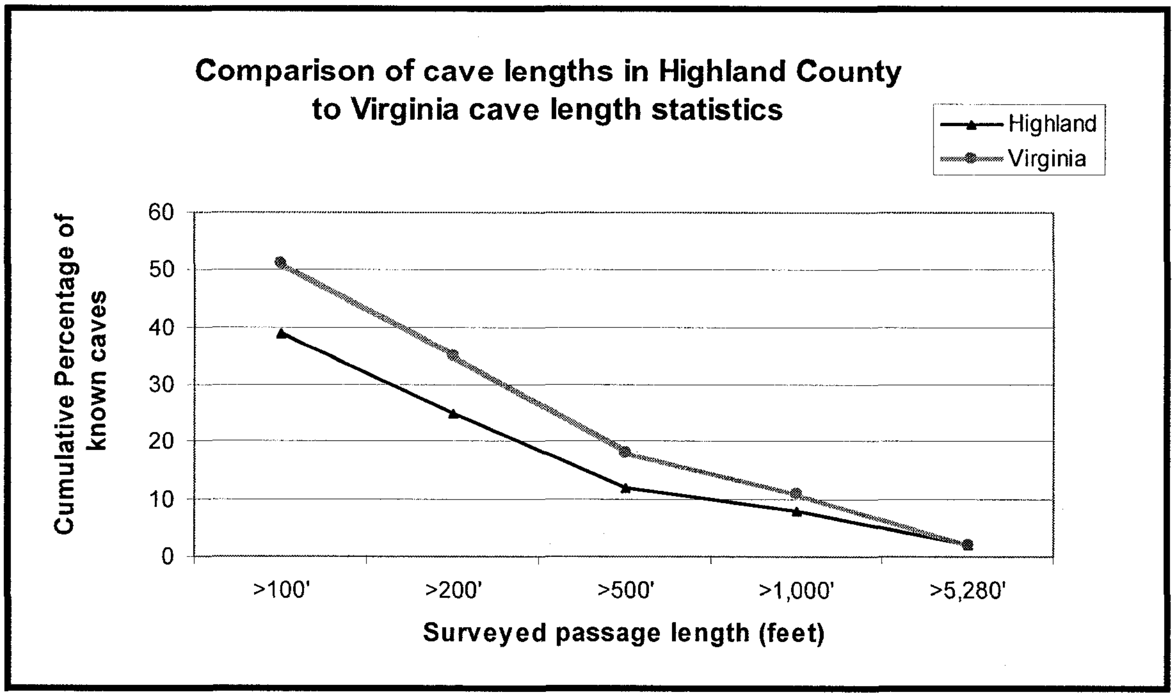


Figure 20. Comparison of cave lengths in Highland County to Virginia cave length statistics. Although Highland has fewer long caves compared to that seen overall in Virginia, the trend of cave lengths mimics that seen statewide. Even the "kink" at caves longer than 500′ can be seen in Highland as well as in the state's statistics.

being longer than 100′ (30 m). Slot fissures tend to be longer with lengths up to 625′ (190 m) and approximately 49% of this type is longer than 100′ (30 m). Branchwork patterns extend up to 9,300′ (2,835 m) long with 86% of them being over 100′ (30 m) and 41% of them longer than 500′ (152 m). Maze networks range from 40′ (12 m) to over 29,000′ (8,839 m) of surveyed passage with 93% of these being over 100′ (30 m) in length and 64% being over 500′ (152 m). In other words, fissures represent the population with the least number of caves over 100′ (30 m). Approximately half of the slot fissures are longer than 100′ (30 m), approximately 86% of branchworks, and 93% of maze networks are over 100′ (30 m) in surveyed length.

Table 3 shows that the most number of fissure caves throughout the county are between 0 and 20′ (6 m) long with none of this type being over 300′ (91 m) long. Slot fissures tend to be longer and show a high frequency at 21′ to 40′ (6-12 m) and again at 101′ to 200′ (31-61 m). They range up to approximately 700′ (213 m) long. The highest number of branchwork caves fall between 201′ to 300′ (61-91 m) long, but almost all development of branchworks range from 101 (30 m) to over one mile. The highest frequencies of maze networks are between 801′ to 2000′ (244-610 m) with some development of maze networks even longer than that. There is almost no development of networks shorter than 400′ (123 m) long.

Table 3. Breakdown of cave types within length increments.
County breakdown of cave types within certain cave length increments. n=191. Percentages do not total 100 percent because pits are omitted from the chart (22% of all Highland caves) and several caves were more than one predominant type.

Total surveyed horizontal length	Fissures	Slot Fissures	Branchwork	Maze Network
0-20′	**13.6%**	2.1%	<1.0%	0
21′-40′	6.8%	**8.9%**	0	0
41′-60′	2.6%	4.2%	0	<1.0%
61′-80′	1.0%	2.1%	<1.0%	0
81′-100′	3.1%	1.0%	<1.0%	0
101′-200′	2.1%	**8.9%**	1.6%	<1.0%
201′-300′	1.0%	4.2%	**3.1%**	<1.0%
301′-400′	0	2.1%	1.6%	0
401′-500′	0	1.0%	1.0%	1.0%
501′-600′	0	1.0%	0	0
601′-700′	0	<1.0%	1.0%	0
701′-800′	0	0	0	0
801′-1000′	0	0	<1.0%	**1.6%**
1001′-2000′	0	0	1.0%	**1.6%**
2001′-3000′	0	0	1.0%	1.0%
3001′-4000′	0	0	<1.0%	0
4001-5,280′	0	0	1.0	0
Over 1 mile	0	0	<1.0%	1.0%

Overall, these data may permit the HCCS to identify areas that are most conducive to the development of maze network and branchwork patterns when exploring for new caves. Because branchwork caves may not be as prominent in Highland County, it may be more productive to concentrate exploration efforts in areas where mazes tend to develop, including areas of low-dipping rocks (preferably horizontal) that have a sandstone caprock. One particular region has been identified by the author and has been disclosed to the HCCS for future exploration.

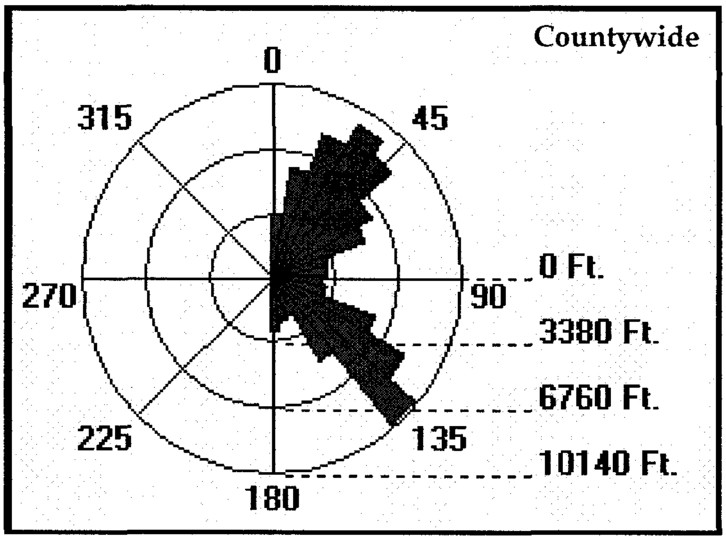


Figure 21. Rose diagram of total surveyed passage length in Highland County.
Rose diagram represents total surveyed passage length of 191 caves in Highland. Rose petals are in 10-degree increments and circles represent passage length in feet (note scale in lower right). Strong directionality is seen in the regional strike direction (N40°E) and the dip directions (either northwest or southeast) suggesting strong joint control of cave passages.

Countywide Predominant Cave Passage Direction

In order to further determine how geologic processes influence cave formation in Highland, Rose diagrams were created to determine overall directions of cave development. Figure 21 shows directions of surveyed passages of all 191 caves used in this study. Passages are abundant in directions of regional strike (N40°E) and regional dips (either southeast or northwest). Data in Figure 21 indicate that the passages are strongly controlled by joints in those two directions.

Because the Rose diagram in Figure 21 is somewhat biased due to long cave lengths, the author devised a method to analyze the frequency of caves oriented in quadrant directions without the length bias (see Analytical Methods for details). Figure 22 denotes the prominent cave passages based on cave frequency instead of cave lengths. These directions were based on a review of individual Rose diagrams and cave maps for each cave. The predominant directions also reflect strong joint control in the regional strike and dip quadrants, NE-SW and NW-SE, respectively.

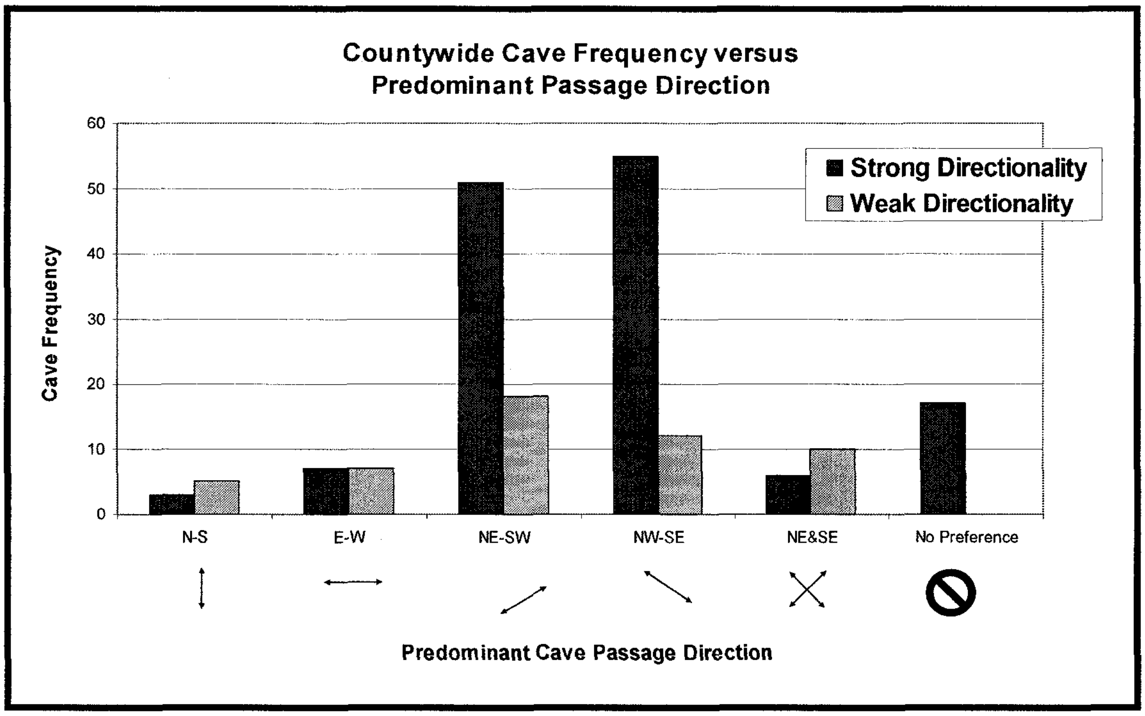


Figure 22. Countywide cave frequency versus predominant cave passage direction
Passage directions based on careful review of Rose diagram and cave maps for each cave. A strong predominance of caves are in both the regional strike quadrant (NE-SW) as well as the regional dip quadrant (NW or SE) also suggesting strong joint control of cave passages.

Table 4. Breakdown of predominant cave types by strata, based on frequency.
Both limestone regions show a high frequency of fissures and slot fissures and relatively similar tendencies of pits and branchwork-type caves. More rooms occurred in Ordovician limestone and more maze networks were found in Silurian-Devonian limestone.

Cave Type	Cave Pattern frequency in Silurian-Devonian strata	Cave Pattern frequency in Ordovician strata
Fissure	**28.3%**	**39.1%**
Slot Fissure	**35.2%**	**34.8%**
Pits	21.4%	23.9%
Rooms	10.3%	17.4%
Maze Network	9.0%	2.2%
Branchwork	15.9%	17.4%
# Caves used in study	**n=145 caves**	**n=46 caves**

Silurian-Devonian vs. Ordovician- Cave Pattern Differences and Similarities

Of the 145 sampled caves in Silurian-Devonian strata (by frequency), 35% of these were slot fissures, 28% were fissures, 21% were pits, 16% were curvilinear and rectilinear branchwork, 10% were rooms, and 9% were maze networks (Table 4). Note that the percentages in Table 4 total more than 100% because many caves were comprised approximately equally of more than one predominant cave pattern. Figure 23 shows these percentages normalized to 100%.

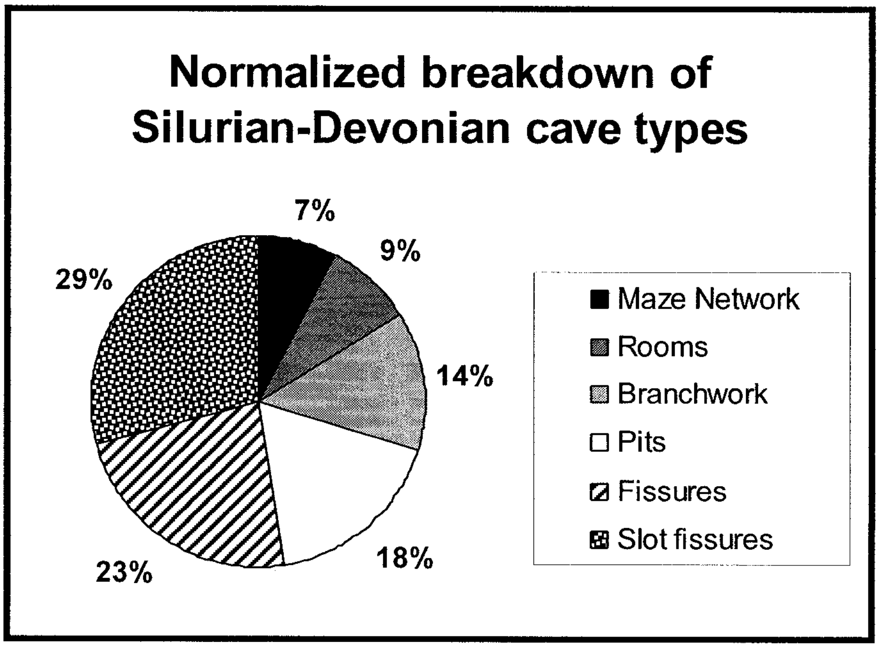


Figure 23. Silurian-Devonian cave types by frequency; values normalized to 100%.
Slot fissures and fissures dominate the cave patterns found in the Silurian-Devonian strata. Maze networks compose the fewest.

Of the 46 sampled caves in Ordovician strata (by frequency), 39% of these were fissures and 35% were slot fissures, 24% were pits, 17% were rooms, 17% were curvilinear and rectilinear branchwork, and 2% were maze network (Table 4). Because these total to more than 100% (again because some caves were placed into more than one category), the percentages were normalized to 100% and are shown graphically in Figure 24.

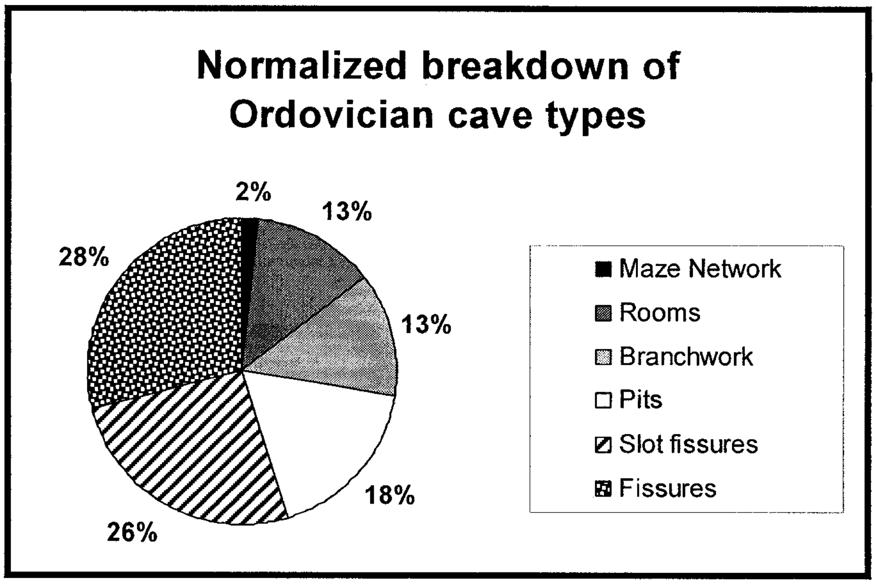


Figure 24. Ordovician cave types by frequency, normalized to 100%. Fissures and slot fissures dominate the cave patterns found in the Ordovician strata. Maze networks also make up the fewest, very similar to that found in Silurian-Devonian strata.

Oddly enough, given the differences in lithologies and structural positions of these strata, both cave sections reflected similar percentages of cave types, with the most frequent being fissures or slot fissures and the least frequent type being maze network. Ordovician strata also tended to have more rooms than Silurian-Devonian strata, while Silurian-Devonian strata tended to have more maze network caves.

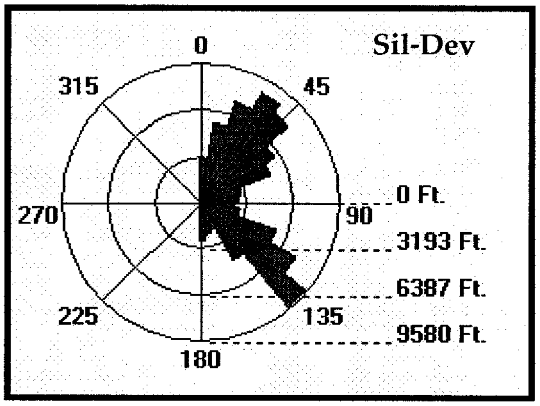
When the cave types were again broken down into increments of total length, similarities could be seen in the passage types associated at particular lengths (Table 5). Fissures dominated in both Silurian-Devonian and Ordovician strata for lengths from 0 to 20′ (0-6 m). Both sections of strata had similar peaks of slot fissure development from 21′ to 40′ (6-12 m) and again around 100′ (30 m) or 200′ (61 m). The frequency of branchwork caves peaked in both strata when cave lengths reached approximately 201′ to 300′ (61-91 m) long. The frequency of maze networks peaked in both strata at around 801′ to 2000′ (244-305 m) of passage length. Silurian-Devonian strata had more range of development of branchwork and maze network-type caves whereas Ordovician strata tended to have specific lengths of these types of patterns.

Table 5. Breakdown of cave types within length increments in Silurian-Devonian and Ordovician strata.
Frequency of cave types within cave length increments. n=145 for Silurian-Devonian and n= 46 for Ordovician. Percentages do not exactly total 100 percent because pits are omitted from the chart and several caves were more than one predominant type. Chart explained further in text.

Total surveyed horiz. length	Fissures		Slot Fissures		Branchwork		Maze Network	
	Sil-Dev	Ord	Sil-Dev	Ord	Sil-Dev	Ord	Sil-Dev	Ord
0-20′	**11.0%**	**21.7%**	2.1%	2.2%	<1%	0	0	0
21′-40′	7.6%	4.3%	**8.3%**	**10.9%**	0	0	0	0
41′-60′	2.8%	2.2%	4.1%	4.3%	0	0	<1%	0
61′-80′	1.4%	0	2.1%	2.2%	<1%	0	0	0
81′-100′	1.4%	8.7%	1.4%	0	<1%	0	0	0
101′-200′	2.1%	2.2%	**10.3%**	4.3%	1.4%	2.2%	<1%	0
201′-300′	1.4%	0	3.4 %	**6.5%**	**2.8%**	**4.3%**	<1%	0
301′-400′	0	0	2.1%	2.2%	2.1%	0	0	0
401′-500′	0	0	1.4%	0	1.4%	0	1.4%	0
501′-600′	0	0	0	4.3%	0	0	0	0
601′-700′	0	0	0	2.2%	<1%	2.2%	0	0
701′-800′	0	0	0	0	0	0	0	0
801′-1000′	0	0	0	0	<1%	0	<1%	**4.3%**
1001′-2000′	0	0	0	0	1.4%	0	**2.1%**	0
2001′-3000′	0	0	0	0	1.4%	0	1.4%	0
3001′-4000′	0	0	0	0	<1%	0	0	0
4001-5,280′	0	0	0	0	1.4%	0	0	0
>1 mile	0	0	0	0	<1%	0	1.4%	0

Silurian-Devonian vs. Ordovician- Predominant Cave Passage Direction

Rose diagrams (2-D) were created to show azimuth directions of passage orientations (Figure 25). Both the Silurian-Devonian and Ordovician strata reflect predominant passage development in the direction of regional strike (N40°E) and regional dip to the southeast or northwest. (Because the diagrams use the 180-degree mode, angles larger than 180 are reversed- see Computer methods). Caves in Silurian-Devonian strata show slightly more caves in the direction of dip compared to caves in Ordovician strata. When plotted by frequency (Figure 26), caves in both sections continued to show strong passage formation in the direction of both regional strike and dip, with caves in Silurian-Devonian strata showing a bit more development in the direction of dip. More caves in the Ordovician strata appeared to have no predominant direction at all. This may reflect the many equi- dimensional rooms and pits in the Ordovician strata that do not show



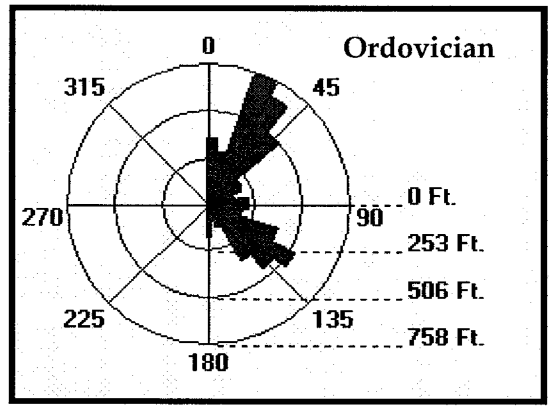
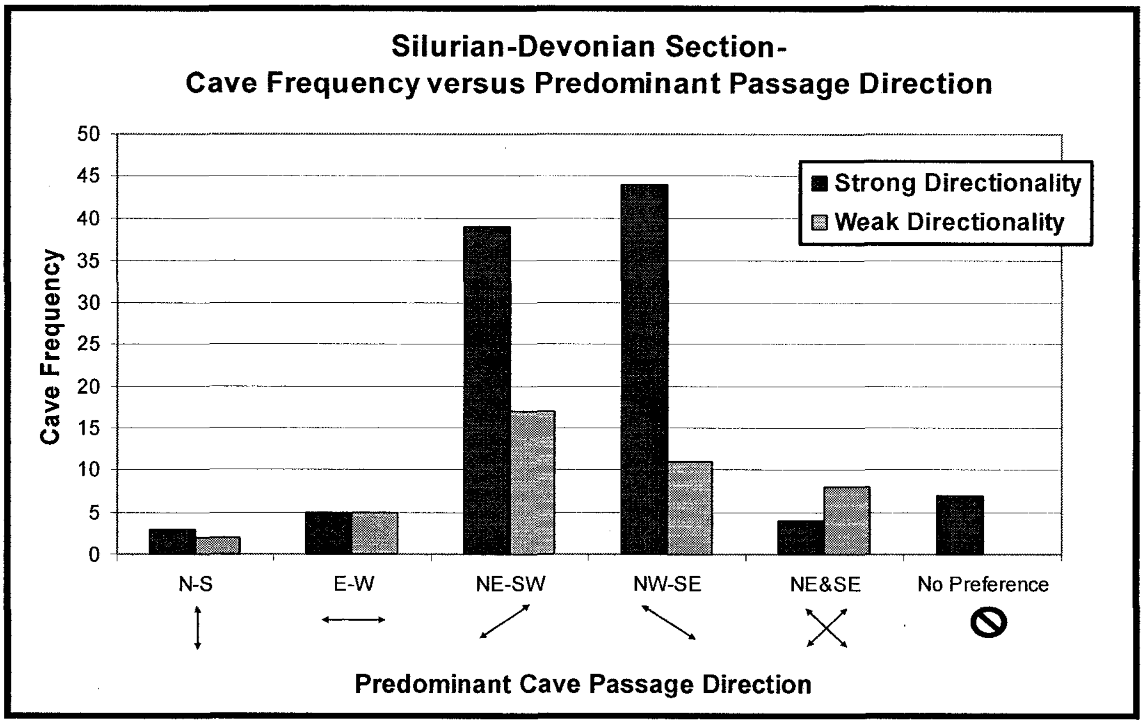


Figure 25. Direction of passages total passage length of caves in Silurian-Devonian and Ordovician strata.
Rose diagram showing passage directions in Silurian-Devonian strata (left) and Ordovician strata (right) by total surveyed passage. Rose petals are in 10-degree increments and circles represent passage length in feet (note scale in lower right). Both show strong joint control in the regional strike (N40°E) and dip directions (northwest or southeast). There appears to be slightly less cave development in the direction of dip in the Ordovician strata, relative to development in the direction of dip.

a predominant direction.

The reader may find it helpful to refer back to Figure 8, which shows the generalized geologic cross section through Highland County. Figure 8 also illustrates the relationship between the two groups of cave-forming strata and their respective elevations. Profile lines are shown on both a topographic map and a generalized geologic map. With the profile, cave development at depth portrayed in the 3-D Rose diagrams in Figures 27 and 28 can be better visualized. Structurally speaking, the Ordovician beds lie near the center of tight anticlines and the Silurian-Devonian beds are exposed in open synclines, with the exception of the anticlinal Bullpasture Mountain.

The 3-D Rose diagrams were created for both limestone sections in order to observe similarities and differences in cave formation at depth (Figure 27). The scales are quite different because more caves are represented in the Silurian-Devonian strata than the Ordovician strata and because there is much more known passage development in the Silurian-Devonian strata. Notice the extensive cave development in the Silurian-Devonian strata at approximately 1,900 feet (579 m) above sea level. This band of extensive cave development represents the longest known cave



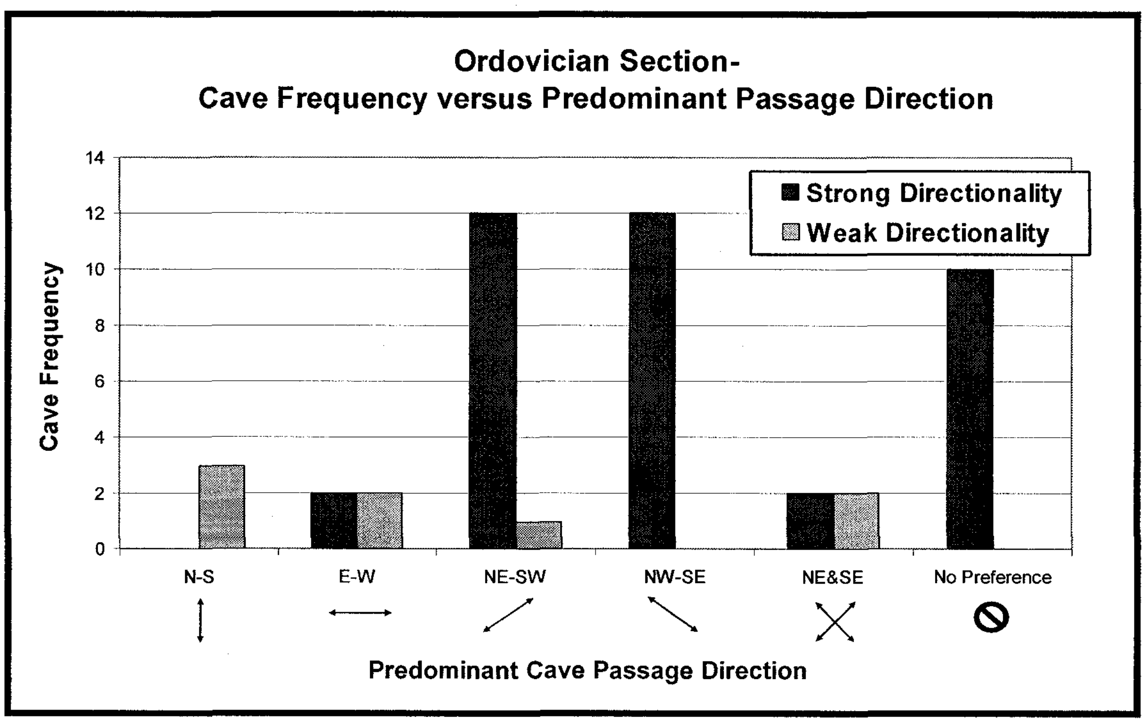


Figure 26. Cave directions in Silurian-Devonian and Ordovician strata, by frequency. Dark grey= strong predominance in the respective directions. Light grey= weak predominance. The Silurian-Devonian and the Ordovician sections both show strong predominant directionality in the NE-SW (regional strike direction) and the NW-SE (regional dip direction) indicating strong joint control. The Ordovician section also shows a strong indication of no preferential direction, as verified by many caves containing rooms. Notice difference in scales. n=146 for Silurian-Devonian and n= 45 for Ordovician.

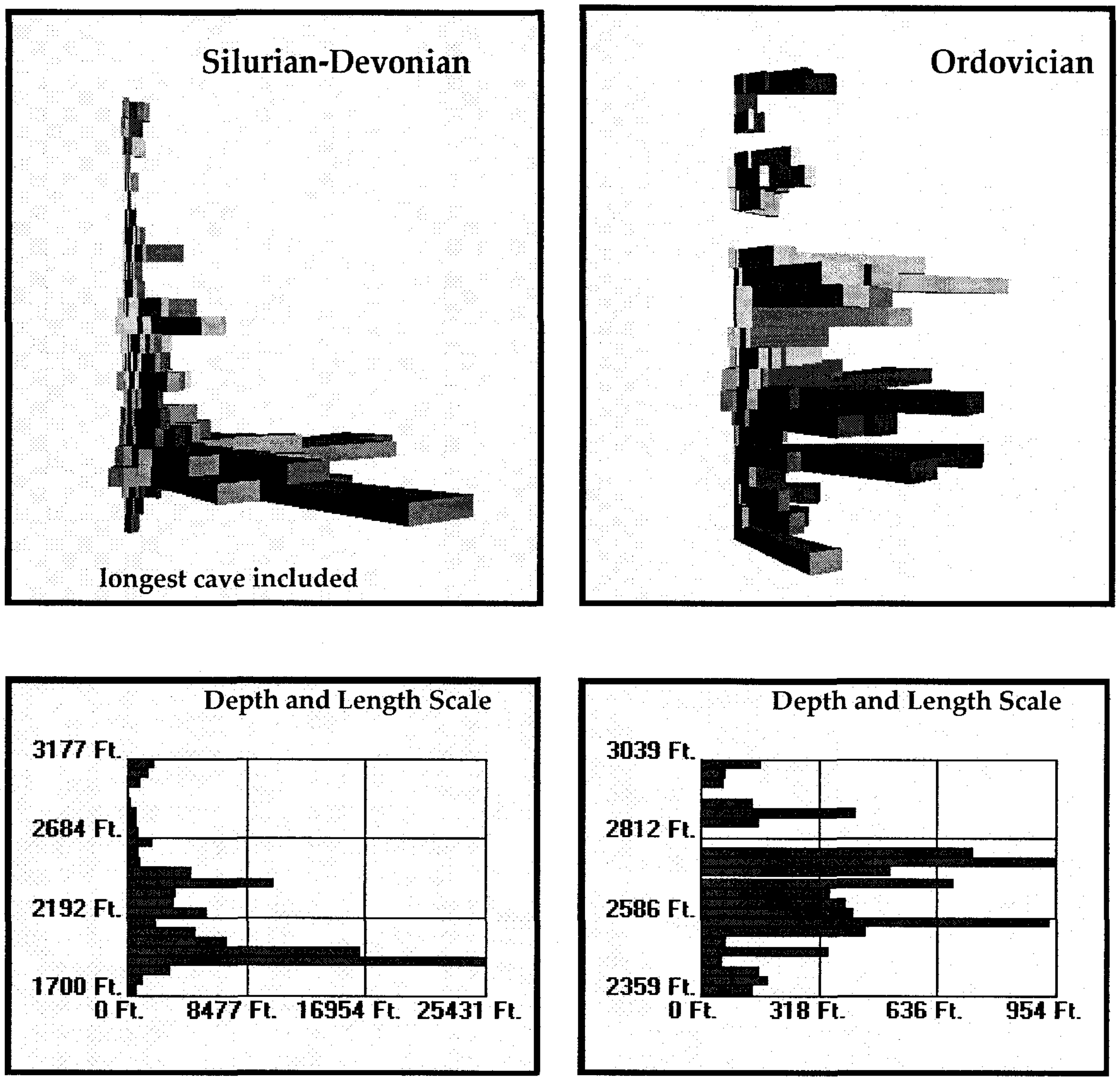


Figure 27. 3-D Rose diagrams and depth scales showing passage formation at depth in Silurian-Devonian and Ordovician strata.

Rose diagrams above show passage formation and respective direction at depth. Below are corresponding depth and length scales. Because of the drastic difference in scales (partly because of the unequal number of caves, partly because of predominance of long caves in the Silurian-Devonian strata), no comparison between these two areas can easily be made.

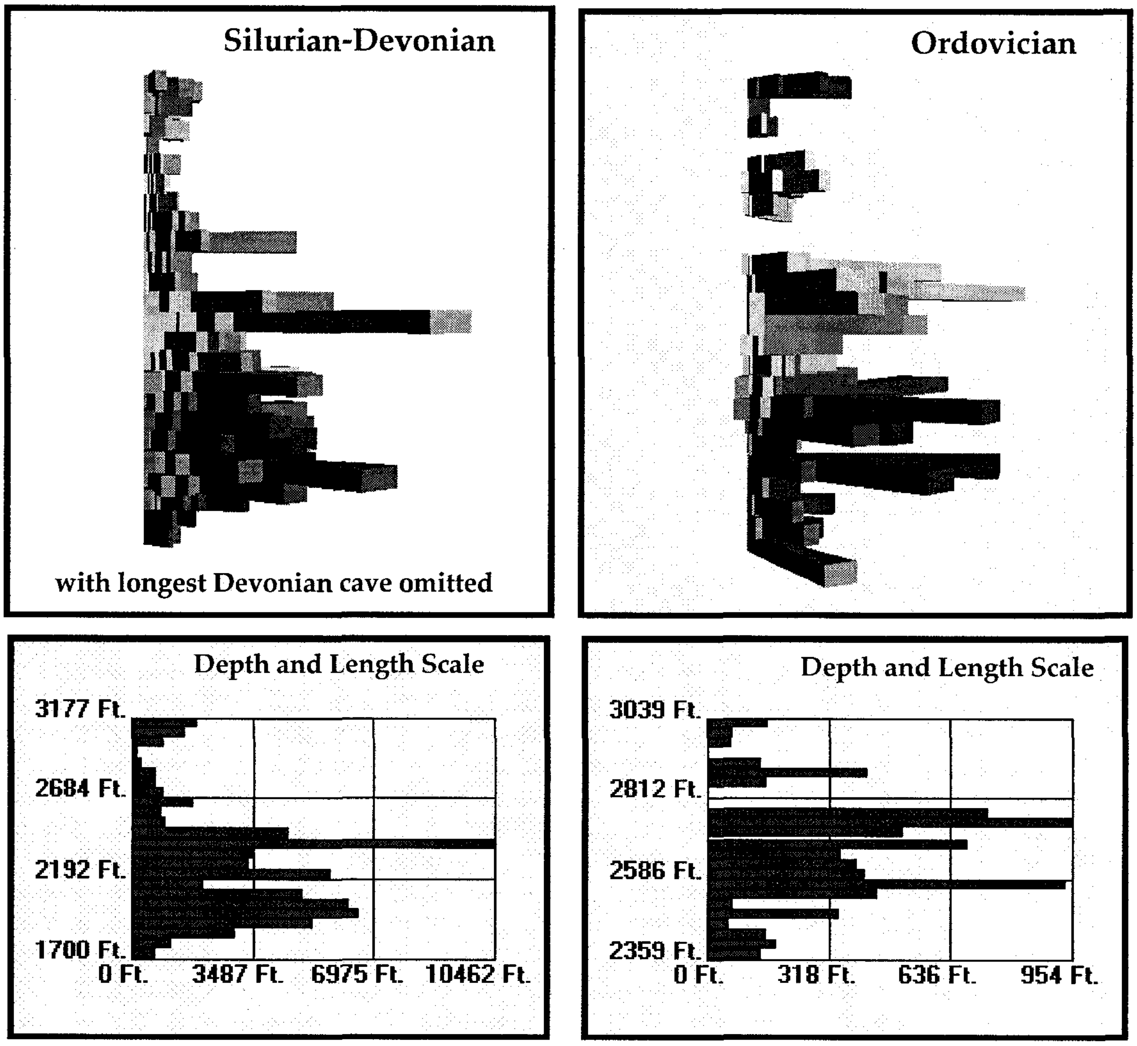


Figure 28. Depth bar of cave development in both sections with longest cave omitted from Silurian-Devonian strata.

cave in Highland County, encompassing over seven miles of passage. This maze network cave lies in very low-angled dipping strata situated in the Burnsville Cove area where cave development is quite extensive (see White and Hess, 1982; Deike, 1960 for works on cave development in the Burnsville Cave area). When this cave was omitted from the 3-D Silurian-Devonian Rose diagram, a better overall representation of cave development at depth appears for that section (Figure 28). Though the scales are still different, over two miles of passage representing several Silurian-Devonian caves can be seen at an elevation of approximately 2,300 feet (701 m) above sea level. In general, cave development in Silurian- Devonian strata ranges in elevation from 1,700 to 3,177 feet above sea level, or about 1,477′ (450 m) of vertical development.

Cave development in Ordovician strata only spans about 680′ (207 m) of vertical development. This does not mean that cave development is deeper in Silurian-Devonian strata, but instead is due to the high relief of the mountains where Silurian- Devonian strata are encountered versus the valley bottoms where the Ordovican limestone is found. Vertical cave development appears to be a mere reflection of the stratigraphy and topography and therefore development in the Silurian-Devonian strata and Ordovician strata do not appear to be occurring along common elevations.

Overall Geologic Influences

Of the 191 caves used in this study, 13% had observable structural deformation such as faulting and folding at the entrance or described in the historical cave report (Figure 29). Several additional caves that were not ultimately used in the study were also observed to have structural deformation at the entrance, and are not included in this percentage. Many of the observed cave passages were situated parallel to fault planes and appeared to be directly influenced by structural deformation processes; however, the majority of the cave passages did not appear to be directly influenced by the local structural deformation at all. Because cave passages were not geologically evaluated in their entirety during this study, individual structural deformation features, such as faults are expected to be a controlling factor in a larger number of caves, but the precise degree of control needs to be further studied.

Joint control of cave passages is the most obvious controlling factor of cave development in Highland County. After evaluating cave maps and COMPASS files in both plan and profile, it was determined that approximately 31% of the caves showed passage formation parallel to strike while 31% showed some passage formation parallel to dip. About 6% showed well-developed passage in both strike and dip directions. Unexpectedly, about 27% showed obvious development along 60/120 degree fractures, characteristics of compressional and shear forces (Figures 30 and 31). Approximately 5% of Highland caves could not be determined what was directly influencing their passage development.

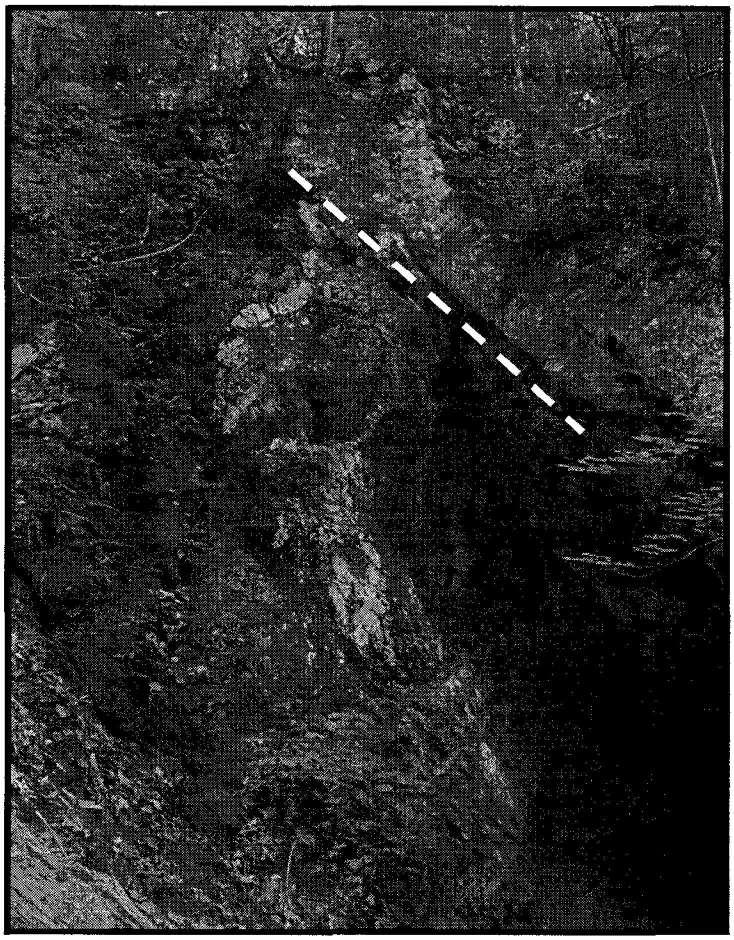


Figure 29. Cave entrance showing structural deformation. The deformation highlighted in this photo (dashed line) lies on a mappable thrust fault shown on a Report of Investigation prepared and provided by the West Virginia Geological and Economic Survey. This cave passage lies parallel to the fault plane and the strike of the mountain (NE-SW). The portion of rock that has been overturned (to the left of the fault) is approximately six feet along the observable diameter.

Cave passages in Highland County are predominantly (92%) within the vadose zone with only 4% of the known caves showing active development in the phreatic zone. Approximately 5% of Highland's caves exhibit characteristics of both active vadose and phreatic development. These observations are consistent with the fact that slot fissures, fissures, pits, and rooms- the types of caves most frequently found in Highland County- all form in areas of vadose recharge.

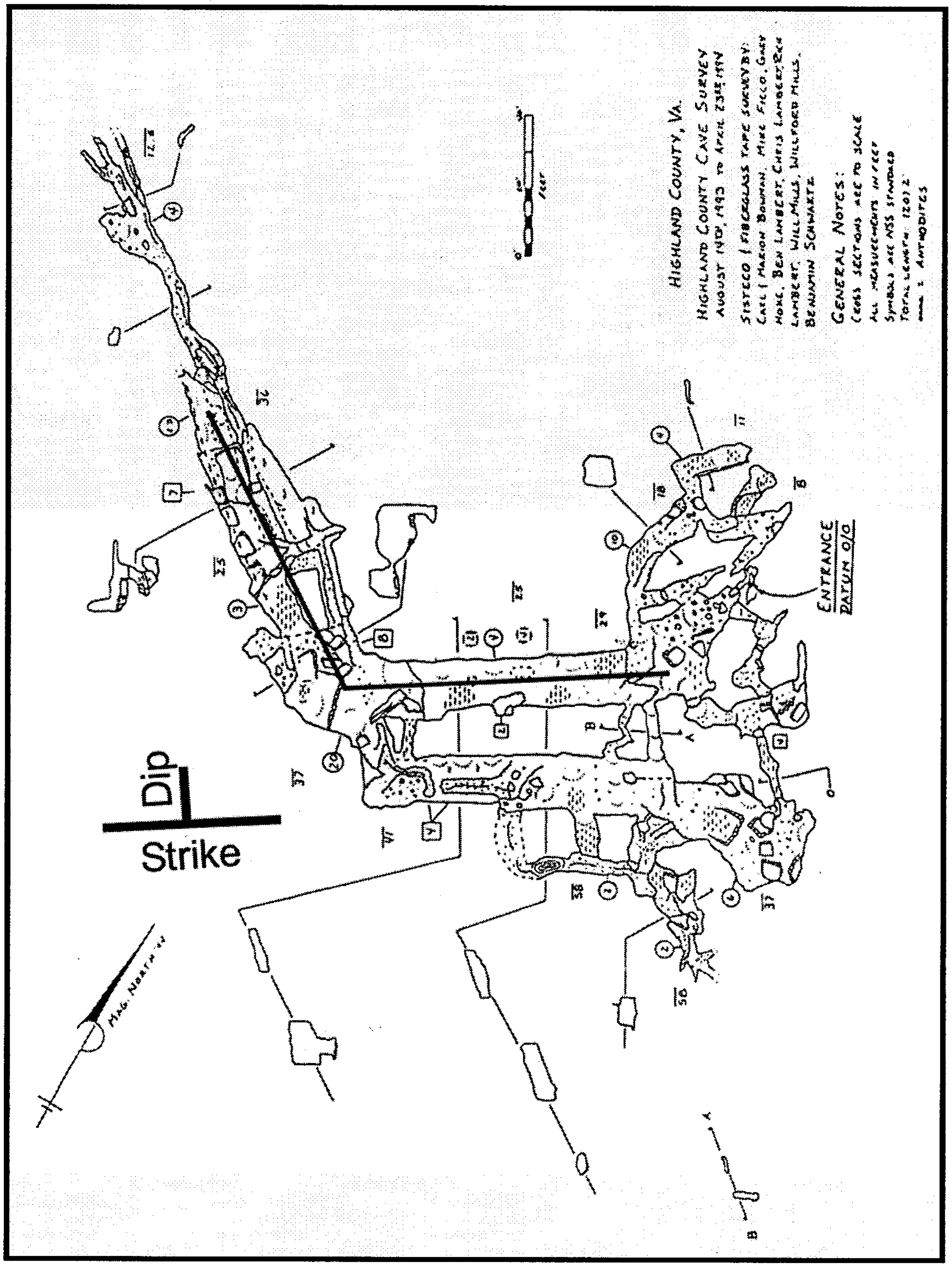


Figure 30. Map of a Highland County cave showing two passages intersecting at approximately 120 degrees.
Dark lines through the middle of the cave represent predominant directions. The angle between them is approximately 120 degrees. Cave location and name not identified due to author's agreement with VSS and HCCS. (After map from Highland County Cave Survey files).

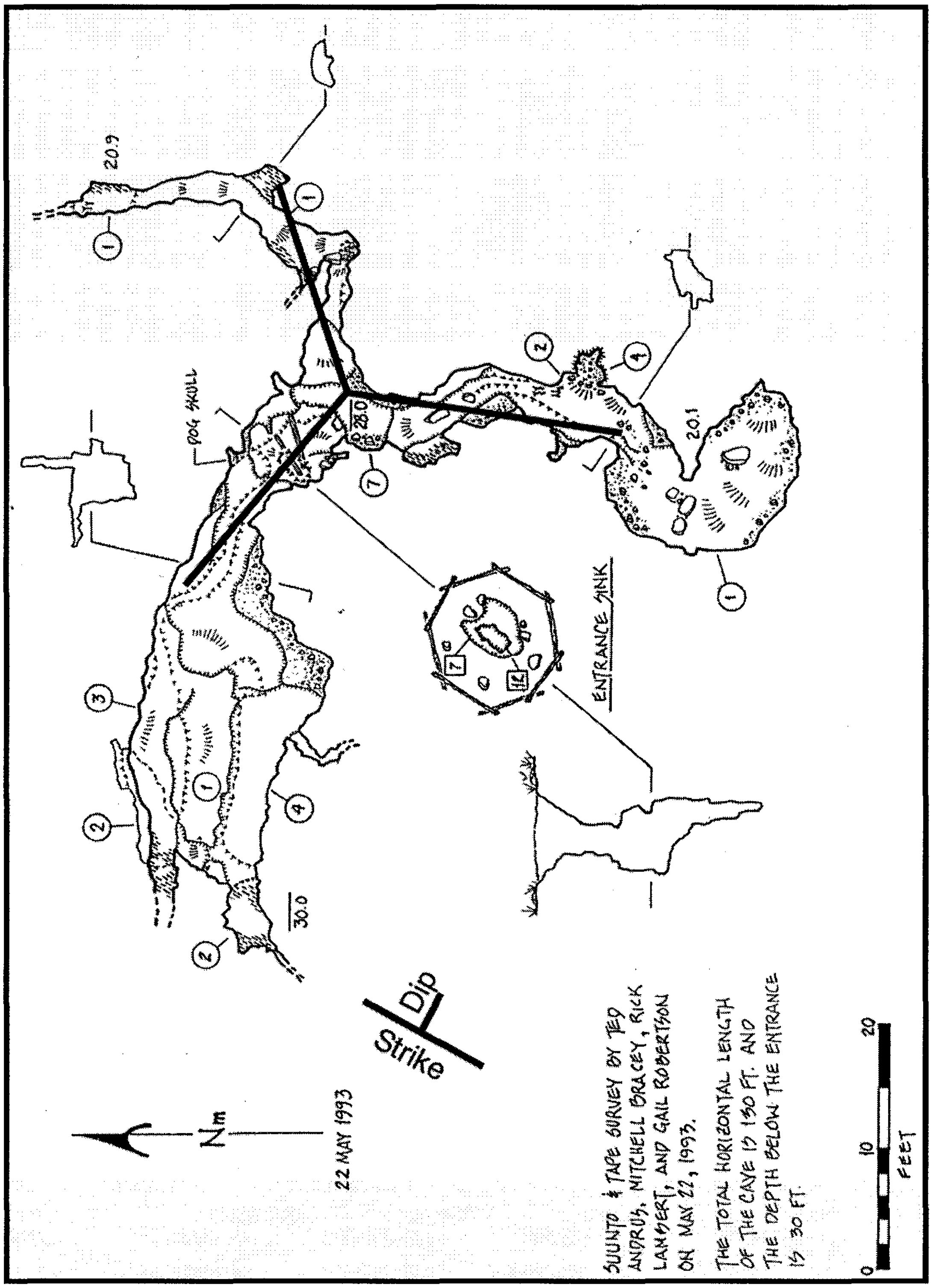


Figure 31. Map of a Highland County Cave showing three passages intersecting at approximately 120 degrees.
Dark lines through the middle of the cave represent predominant directions. The angles between them are approximately 120 degrees. Cave location and name not identified due to author's agreement with VSS and HCCS. (After map from Highland County Cave Survey files).

Interestingly enough, when prominent directions were compared to vadose or phreatic components of development, over 25% of the caves formed under vadose conditions appeared to be parallel to strike. (In some instances, it was difficult to determine if passages were parallel to strike or actually parallel to fractures forming at 60-degrees). As per EPA (2002) and Palmer (2003a), vadose caves in dipping strata tend to form in the direction of dip. Although the anomalous vadose caves in Highland County that formed parallel to strike contain vertical characteristics of vadose development, it is unclear if the caves formed under present vadose conditions or if they developed under ancient phreatic conditions when water tables were higher. Most of the caves in question were located at elevations that could realistically fall into the latter category. As the regional surface erosion and valley incision removed overlying rock from the landscape, the water table would have migrated downward through these rocks. Future studies relating the ages of cave development and regional denudation rates are needed to resolve this discrepancy.

Discussion

In order to assess whether results of previous studies accurately predict cave morphology and recharge patterns in Highland County, a recap of findings is necessary to compare overall pattern types to recharge sources. Also, previous ideas of geologic forces on cave development must be reviewed in order to get a complete idea of the controls of speleogenesis in Highland County.

Although branchwork cave patterns are the most common by frequency and length in most karst aquifers, fissures and slot fissures accounted for 65% of Highland caves by frequency and maze networks accounted for 50% by total surveyed length. This anomaly to Palmer's (1991) findings may be evident because the worldwide patterns were determined for caves longer than 3 km, and Highland only has a handful of caves longer than 3 km. Another possibility for the difference in predominant pattern type could be that there may be many unknown branchwork cave systems yet to be discovered in Highland County. Furthermore, there were several known branchwork caves that were not included in this statistical study. By including the remaining known branchwork caves as well as undiscovered branchworks, the findings in Highland County could more resemble the worldwide findings by length, but doubtfully by frequency. What could also be occurring to explain the inconsistency in pattern type is that the fold-induced joint patterns in Highland County may dominate the subsurface to the point that they override the capability of branchwork patterns to form, even in the sinkhole plains of the Ordovician strata where the carbonates are exposed on the crest of a tight anticline.

Fissures throughout the county were primarily 0′ to 20′ (0-6 m) long and slot fissures tended to be somewhat longer, with most of this cave type being between 21′ to 40′ (6-12 m) long or 101′ to 200′ (31-61 m) long. Branchwork patterns were mostly found to be between 201′ and 300′ (61-91 m) long and maze networks tended to be longest with most of this cave type between 800′ to 2000′ (244-610 m) long. This pattern appears to be a direct result of recharge effects on the cave systems. Palmer (2003) indicates that karst porosity is highest near the land surface and diminishes further down, which may explain why fissure-type caves are so numerous. Also, many fissure caves do show evidence of continuing beyond widths capable of human entry, further showing the possibility that fissures are more numerous merely because they are near the surface. Fissures tended to be short, consistent with Palmer's (2003b) finding that the number of fractures and partings diminished in width and number with depth. Slot fissures are canyons or canyon-like and tend to be deeper and longer than fissures, indicating that they are probably fissures that are just more developed. Branchwork caves resemble dendritic surface streams with several tributaries converging into a main trunk. The catchments are larger for branchwork patterns than slot fissures and fissures and are expected to be longer than the two. Maze networks tend to form in flat-lying strata with all fractures subjected to simultaneous recharge, effectively allowing more surface area to be affected by dissolution, thus resulting in longer cave passages.

Approximately 50% of the caves that could be classified as halls and narrows exhibited vertical halls parallel to strike, similar to Osborne (2003). However, the other half of those caves showed vertical halls stairstepping parallel to the dip direction and thus perpendicular to strike. This pattern appears to show that fractures are primarily influencing water movement and bedding is a secondary influence. Almost all passages were observed to be vertical and not slanted with bedding, again showing the influence of fractures on speleogenesis.

Cave patterns that were revealed in Highland County do not mimic predominant patterns seen worldwide; however, a comparison of cave lengths in Highland shows a very similar trend to cave lengths seen throughout Virginia. Although there are fewer long caves in Highland than found statewide, the overall trend between Highland and Virginia cave lengths is almost a mirror image. This finding could perhaps encourage future studies to compare statewide cave patterns and cave lengths in order to further understand the similar trend seen between Highland and Virginia.

Two-thirds of cave passages in Highland County formed parallel to regional strike and/or dip and approximately one-third exhibited fractures intersecting at approximately 60 and/or 120 degrees. These fracture sets are indicative of compressional and shear forces acting upon the strata. Klimchouk and Ford (2000) indicate that in folded rocks, strike-oriented joints are usually dominant along the crests and troughs of the fold while the limbs of the fold show mixtures of dip, strike, and 60-degree shear joint systems. The strong evidence of joint control of cave passages was very much expected, however the observance of at least one-third of the mapped caves exhibiting intersections at 60 or 120 degrees was not.

Finding that fissures and slot fissures are the majority cave type in Highland (by frequency) affirmed that this pattern was "typical of many caves stretching in a linear alignment", a trend that Highland cavers had noted over many years (HCCS/VSS cave report #2896). In fact, Highland County cavers have generally observed that the typical fissure caves were notorious for being short and that only the relatively scarce branchwork and maze networks tended to be much longer. Stafford et al. (2005) found fissure caves to be associated with various types of brittle deformation such as faults and brittle failure. In Highland, it appears that the majority of fissure caves result from both brittle failure (fracturing) and somewhat from faulting. More research should be done to verify this hypothesis, because a geologic evaluation within each cave was not performed. However, several cave passages in Highland were found to follow fault planes (such as that in Figure 29), and tended to be branchwork in nature with perennial water flow. Most of the observed local structural deformation (such as faulting) and other evidence of local geologic processes, however, did not appear to greatly alter passage direction or influence passage genesis, possibly due to secondary mineralization preventing dissolution or pilfering of nearby conduits. One spectacular example is of an igneous dike intruding perpendicularly into limestone. The dike is obvious on both sides of well-developed cave passage indicating that the intrusion did not alter passage formation in the least. Large local faults and regional structures appear to have more prominent effects on speleogenesis than small local structures. Many fissure and slot fissure caves over 100′ (31 m) in surveyed length appeared to be more of a rudimentary maze network, only lacking closed loops. (In other words, the passages consist of a few "L" shaped passages, versus connected "square" passages). Most of the observed fissure caves contained a main single passage with narrower and mostly equi-spaced side passages at approximately 90 degrees or 60/120 degrees. Both situations (90 degree intersections and 60/120 intersections) are indicative of preferential flow along fracture partings associated with folding. Overall, there have been observed instances of direct alteration by faults, though it appears that the majority of cave formation is by solutional widening of fractures and joints, with minimal effects of faulting.

There were fewer differences between Silurian-Devonian strata and Ordovician strata than were predicted. Although strong joint control was expected in both sections, it was surprising to find caves in both areas developing quite prominantly in both directions of strike and dip. Fissures and slot fissures were found most frequently in both strata followed by pits and branchwork-type caves which were also found in similar frequencies. Ordovician strata had a bit less development in the direction of dip relative to strike and had more rooms than that found in Silurian-Devonian strata. Another significant difference was the stronger development of maze caves in the Silurian-Devonian strata than that found in the Ordovician strata. The large maze network caves that were found in Silurian-Devonian strata tended to have relatively low dip angles and a sandstone caprock- either the Healing Springs sandstone (a basal unit of the New Scotland limestone in the Helderberg Group) or the Clifton Forge sandstone, two thin sandstone units approximately 10-15′ (3-5 m) thick that appear in the Keyser Limestone unit. The Ordovician rocks were more tightly folded into anticlines with higher dip angles and fewer clastic interlayers while the Silurian-Devonian rocks tended to be troughs of open synclines.

The presence of the expansive sinkhole plains and lack of surface streams in the long lowlands at the crest of the breached anticline would lead one to expect numerous branchwork-type caves existed in the Ordovician strata. On the contrary, the fissures and slot fissures dominated the subsurface by frequency. The large number of fissures may be a result of the tight folding of the Ordovician strata, thus allowing the fissures to capture most of the recharge before branchwork patterns formed. Also, there may be many unknown branchwork cave systems yet to be discovered in the Ordovician strata. There were several known branchwork caves that were not included in this statistical study. By including the remaining known branchwork caves as well as undiscovered branchworks, the findings may reflect the expectation of more branchworks in the Ordovician strata by length, but doubtfully by frequency. Cave formation at depth between the two strata did not appear to share a particular elevation and appeared to merely reflect stratigraphy and surface topography.

The majority of caves in Highland County appear to be influenced by diffuse recharge, with less influence by allogenic recharge. The overwhelming abundance of cave shapes comprised of maze networks, vertical shafts, and canyons (pits, fissures, and slot fissures) support this contention as well as the abundance of fractures caused by folding (Figure 4). There also appeared to be direct influence by allogenic recharge such as sinkholes or sinking streams, which tended to form numerous fissures and several branchworks. However, the overall scarcity of branchwork caves, especially in the sinkhole plains of the Ordovician strata, may suggest that the fold-induced joint patterns dominate the subsurface to the point that they impede the formation of branchwork patterns.

Vadose recharge appears to be the most active subsurface influence on dissolution of Highland caves. Overland runoff is funneled through the soil, epikarst, fissures, sinkholes, and sinking streams and enters the joints that resulted from compressional and shear forces. Resulting fractures occur parallel to strike, dip, and in joint sets that intersect at 60/120 degrees, with fissures and slot fissures being more numerous near the land surface. Modification of fractures and obvious joint control of speleogenesis in the direction of strike and dip is extremely apparent in Rose diagrams and cave map analysis. Bedding appears to also have some influence in cave development, but not always in the fashion detailed by Osborne (2003). About 50% of halls and narrows showed halls forming parallel to bedding rather than to strike. Thus bedding is influencing cave development, but brittle deformation and the geological processes that incurred the folding are the main controlling factors of speleogenesis in Highland County, Virginia.

FUTURE WORK

Future works that may directly result from this study include but are not limited to:

1) Continue to interpret local stratigraphy, especially in cave-bearing areas.
2) Overlay cave passages in GIS onto Digital Elevation Model (DEM) of Highland County. If stratigraphy can be determined through depth, this will reveal 3-D cave development emphasized by stratigraphy rather than geologic processes alone.
3) Measure and map faults and fractures and determine, with more detail, their influence on speleogenesis.
4) Compare topography to locations of cave passage (with special attention to the extents of catchment areas). This may illustrate how topography affects occurrence of cave passage.
5) Utilize the results of this study to create a conceptual model of the county's hydrology.
6) Continue to update and collect karst database information- especially relating to recharge and discharge areas. The latter two will ultimately facilitate future hydrologic studies, including dye traces, in the area.
7) Search for new caves in areas that were denoted as "potential cave areas".
8) Compare statewide cave patterns and cave lengths to further understand the similar trend seen between Highland and Virginia.
9) Determine the extent of vadose development parallel to strike, which is inconsistent with the idea that this type of development tends to be in the direction of dip.

CONCLUSIONS

When mountain building occurred during the Alleghenian Orogeny, Ordovician, Silurian, and Devonian rocks were uplifted, folded, and faulted. Groundwater was then able to run through fault planes, bedding planes, and fractures and dissolve cavities that trended parallel to regional strike (N40°E) and dip (northwest or southeast) and at intersections of 60 and 120 degrees. These angles of intersection proved consistent with that provided by Klimchouk and Ford (2000), though it was expected to only observe passages parallel to strike and dip. As Sasowski (1999) outlined, structural geology in Highland County primarily controlled speleogenesis by the original folding and faulting of rocks and secondarily by the resulting planar fractures including joints, bedding planes, and faults. Although branchwork cave patterns were more frequently found worldwide by both frequency and total length (Palmer, 1999), this was not the case in Highland County. Fissures and slot fissures dominated the spectrum by frequency and maze networks held the most total passage. Interestingly, halls and narrows in Highland County tended to form opposite to that found by Osborne (2003) with 50% of such caves forming with halls parallel to dip instead of strike. Recharge sources were overall consistent with that outlined by Palmer (1999, 2003a, 2003b). An exception to this was that caves in the Ordovician strata tended to be fissure-type instead of branchwork, despite the extensive sinkhole plains in this strata. Caves in the phreatic zone tended to form consistently with Palmer (2003a) and EPA (2002) in that phreatic caves tended to develop along strike. Vadose cave passages demonstrated a strong down-dip component as influenced by groundwater's gravitational influence, however approximately 25% of these types of caves appeared to trend along strike rather than dip. Most caves appear to form due to diffuse recharge rather than surface stream flow entering into sinkholes.

Overall, caves in Highland County are most affected by brittle deformation, especially fracturing, that resulted from folding of the strata. These fractures appear to supersede the expected development of branchwork caves and perhaps change the expected direction of caves in the vadose zone. Joint control is mostly in the directions of regional strike and dip, but are very often seen intersecting at 60/120 degrees.

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APPENDIX A- GLOSSARY OF TERMS

Benthic macroinvertebrate bioassessments: Assessments of aquatic organisms that are larger then microscopic invertebrates, such as insects, crustaceans, mussels, snails, or worms that live on the bottom of streams. These benthic communities help scientists assess the ecological health of freshwater streams and rivers.

Brittle strain: Strain in which a rock body breaks under stress.

Carbonates: Mineral compounds with the fundamental structure of CO_3^{-2} such as Calcite ($CaCO_3$). Also, sediments/rocks formed of the carbonates of calcium (limestone) or magnesium (dolomite).

Clastics: Pertaining to a rock or sediment composed mostly of fragments from pre-existing rocks or minerals and transported some distance from their place of origin.

Epikarst: the upper surface of karst that consists of a complex system of interconnecting fissures that collects and transports surface water underground; depths can range from a few centimeters to tens of meters (Karst Management Training Handbook, 2001).

Hydrostatic pressure: The pressure exerted by a column of water (at any point within that body of water) at rest

Hypogenic: Processes stemming from deep within the Earth. Hypogenic karst results from a source produced at depth (CO2 or H2S) without the direct influence of surface recharge (Audra et al., 2007).

Impaired waters: Riverine, lacustrine or estuarine waters that do not meet one or more of the designated uses for water (VDEQ, 2006).

Plastic strain: Strain in which a rock body is molded or bent under stress and does not return to its original shape after the stress is released.

Recharge: The processes involved in adding water to the saturated (phreatic) zone. Also pertains to the amount of water added to this zone (Bates and Jackson, 1984).

UTM coordinate: Universal Transverse Mercator projection and grid system adopted by the U.S. Army in 1947 which divides the earth into 60 vertical zones. These zones extend from a latitude of 80° S to 84° N. (Polar regions use the Universal Polar Stereographic (UPS) grid system). Each of the 60 vertical zones is 6 degrees of longitude wide, starting at the International Dateline (longitude 180°) and moving east. Each zone is then divided into horizontal bands of 8 degrees of latitude. These horizontal bands are lettered, south to north, beginning at 80° S with the letter C and ending at 84° N with the letter X. Letters I and O are omitted to avoid confusion with the numbers one and zero. The horizontal band lettered X spans 12° of latitude, instead of 8°. A square grid is then superimposed onto each zone so that the vertical grid lines are parallel to the center of its respective zone. UTM grid coordinates are read in meters to the east and the north. Highland County, Virginia is in UTM Zone 17 S. (Maptools, 2002)

APPENDIX B- DETAILED GEOLOGIC MAP AND ABBREVIATED LITHOLOGIC DESCRIPTIONS

Map on page 73 includes northwestern tip of Highland County, Virginia and abbreviated lithologic descriptions taken from Geologic Map of the Virginia Portion of Elkins 30x60 Minute Quadrangle (Rader and Wilkes, 2000). Scale as noted on map.

Map on page 74 includes the remaining portion of Highland County, Virginia. The county is outlined in black and is taken from Geologic Map of the Virginia Portion of the Staunton 30x60 minute Quadrangle (Rader and Wilkes, 2001). Scale as noted on map.

EXPLANATION

MISSISSIPPIAN

Pocono Formation

Sandstone, white to medium-gray, f... coarse-grained, medium- to thick-bedded, often cross laminated in thick sets... ess 500 to 700 feet

DEVONIAN

Hampshire Formation

Shale, mudstone, siltstone, and sand... Shale, mudstone, and siltstone dusky- to grayish-red, in part micaceous. Sa... e, medium- to brownish-gray, thin- to thick-bedded, cross laminated, in p... aceous and feldspathic, 5-inch to 3-foot beds of conglomerate common ne... top, no reported fossils. Basal contact placed above the youngest fossil... sandstone and shale of the Foreknobs Formation, overlain by redbeds. Thi... approximately 2000 feet

Foreknobs Formation

Sandstone, siltstone, and minor... interbedded. Sandstone, brownish-gray, medium- to coarse-grained, mediu... thick-bedded in part cross laminated, conglomeratic beds common, sands... most abundant in the upper part of the formation; many beds very fos... ss. Siltstone, medium- to thick-bedded, dominant in lower part of unit. S... interbedded with sandstone and siltstone throughout section. Brownish-red s... common in upper half of section. Basal contact mapped at the base of foss... is sandstone underlain by micaceous shale and thin-bedded siltstone. Thickness... ximately 2200 feet

Brallier Formation

Shale, siltstone, and minor sandst... nterbedded dark-gray to greenish-gray, weathers light-brownish-gray; grai... increases upward in section; sandstone more abundant in upper part o... tion, thin- to medium-bedded, sparsely fossiliferous. Base of the formation... l at the top of black to gray shale of the Millboro Shale. As mapped in Hig... County, the Brallier is equivalent to the Scherr Formation of Dennison (1996... kness 1000 to 1800 feet

Millboro Shale, Tioga Ash, a... edmore Formation, undivided

Millboro Shale: shale, black, fi... weathers in thin papery plates, contains abundant pyrite, fossiliferous layer... ncretions locally present (Purcell Member of Dennison, 1996). Thickness 400 t... feet. **Tioga Ash:** alternating gray, silty shale and siltstone, brown, bentoni... calcareous tuff; and fissile, black shale. Thickness 10 to 20 feet. **N... re Formation:** dark-greenish-gray, fossiliferous shale and calcareous n... se with thin (3 to 8 feet) black shale at base. Thickness approximately 120... base of map unit placed at top of gray quartzarenite of the Ridgeley Sands...

uncon... ity

SILURIAN

Devonian and Silurian rocks, undivided

Ridgeley Sandstone: quartzarenite, light- to yellowish-gray, fine- to coarse-grained, locally conglomeratic, thin- to thick-bedded, generally cross laminated, calcareous cement, friable when weathered; fossiliferous, commonly contains molds of shells. Thickness ranges from 30 to 100 feet. **Helderberg Group:** limestone, light- to dark-gray, fine- to coarse-grained, laminated to thick-bedded, with black, nodular chert and white to light-gray, blocky chert; upper portion of the unit argillaceous, lower part of the unit sandy (locally a sandstone, Healing Springs Sandstone Member), base defined by a coarse-grained, gray limestone with large white to pink crinoid stems; locally very fossiliferous; thickness ranges from 100 to 200 feet. **Keyser Limestone:** medium- to dark-gray, fine- to coarse-grained limestone with abundant fossils. Clifton Forge Sandstone Member near middle, argillaceous near base, may contain laminated beds similar to the underlying Tonoloway Limestone in lower portion, sparse, small black chert nodules common, thickness ranges from 75 to 150 feet. **Tonoloway Limestone:** upper and lower members, medium- to dark-gray, fine-grained, laminated, mudcracked limestone with sparse fossils (ostracodes and rare brachiopods); middle member, medium-gray, fine- to medium-grained, abundant algal structures; thickness ranges from 200 to 300 feet. **Wills Creek Formation:** light- to medium-gray, fine- to coarse-grained, fossiliferous limestone, gray, calcareous siltstone, greenish-gray, calcareous mudstone; all lithologies weather to a yellowish-gray shaly residue; thickness approximately 120 feet. **Williamsport Sandstone:** quartz sandstone or siltstone, with *Arthrophycus alleghaniensis* near the base; thickness ranges from 15 to 25 feet. **McKenzie Formation:** medium-gray, yellowish weathering, calcareous shale and limestone, locally very fossiliferous, thickness, approximately 165 feet.

Keefer Sandstone and Rose Hill Formation, undivided

Keefer Sandstone: sandstone, light-gray, fine- to coarse-grained, locally conglomeratic, cross laminated, quartz cement or overgrowths, thin green to purple shale beds near base, sparsely fossiliferous (*Skolithos*, *Arthrophycus*); thickness ranges from 8 to 20 feet, thickens in a southwesterly direction. **Rose Hill Formation:** Sandstone and shale. Sandstone, light-gray to dusky-red, fine- to coarse-grained, cross laminated, gray sandstone identical to the overlying Keefer and the underlying Tuscarora, very resistant to weathering, makes ledges. Shale, green, yellowish-brown, and dusky-red, commonly contains limonitic lenses from the weathering of thin limestone beds; fossiliferous; thickness 300 to 500 feet.

Tuscarora Formation

Sandstone and quartzite. Sandstone, light-gray, weathers rusty brown, fine- to coarse-grained, commonly conglomeratic, clasts 0.25 to 0.5 inch, thin- to thick-bedded, cross laminated, quartz cement, matrix less than 1% Quartzite, light-gray, fine- to medium-grained, cemented by overgrowths, thick-bedded. Thin, red, green, or purple shale near base and top of unit. Sandstone generally overlain by quartzite. Contacts gradational, basal contact mapped at the base of the oldest thick sandstone bed, upper contact mapped at the first thick shale sequence overlying a thick quartzite. Thickness 75 to 125 feet.

ORDOVICIAN

Juniata Formation

Sandstone, dusky-red, fine- to medium-grained, cross laminated, in part feldspathic. Sandstone, light-gray to white, fine- to medium-grained, thick-bedded, cross laminated, base often contains red shale clasts. Shale and mudstone, dusky-red, weathers lumpy. Thickness 250 to 300 feet.

Reedsville Shale and Dolly Ridge Formation, undivided

Reedsville Shale: Upper 50 to 100 feet brown, medium- to coarse-grained sandstone fossiliferous. Lower 300 to 400 feet calcareous, gray shale and mudstone with interbedded lenticular fossiliferous limestone. **Dolly Ridge Formation:** Upper 300+ feet interbedded argillaceous limestone and dark-gray shale. K-bentonites present, fossiliferous. Lower 100 feet interbedded argillaceous limestone and olive-gray claystone (Eggleston Limestone of previous reports).

Ordovician limestones, undivided

Limestone, light- to dark-gray, very-fine- to coarse-grained, locally with black chert nodules and thin beds, several K-bentonites, fossiliferous, lower 100 to 150 feet dolostone or dolomitic limestone with thin ash grey shale beds, black and gray chert nodules. Thickness ranges from 500 to 800 feet.

unconformity

Beekmantown Formation

Dolostone, medium- to light gray, weathers very-light-gray, fine-grained, medium- to thick-bedded, weathered surfaces exhibit a "butcher-block" structure, sparse fossils; limestone, medium-gray, fine-grained, fossiliferous, light- to medium-gray, fine-grained, laminated dolomitic limestone and dolostone with mottled beds, lenses of gray chert common, upper contact unconformable, lower contact not exposed in this area.

KEY

CONTACTS

Exposed, approximate, or inferred

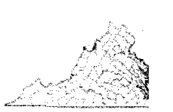
FAULTS

Exposed or approximate, tick mark indicates dip direction.

ATTITUDE OF ROCKS

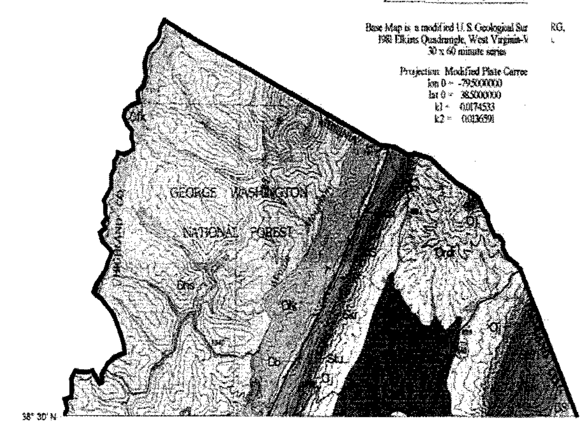
Strike and dip of inclined bedding

Strike and dip of overturned bedding



Base Map is a modified U.S. Geological Sur... RG,
1981 Elkins Quadrangle, West Virginia-V...
30 x 60 minute series

Projection: Modified Plate Carree
lon 0 = -79.500000
lat 0 = 38.500000
k1 = 0.0174533
k2 = 0.0136591



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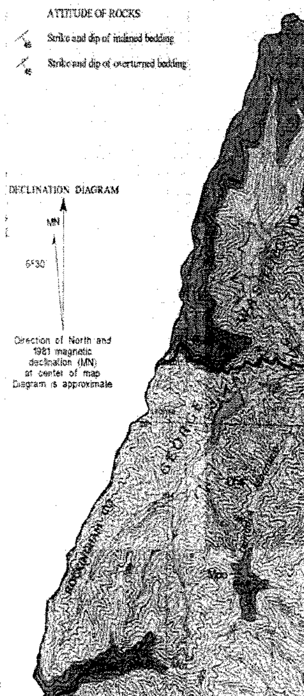
This map was compiled digitally and the geospatially referenced files are available from the Division of Mineral Resources, P. O. Box 3667, Charlottesville, VA 22903.

DECLINATION DIAGRAM

MN

6°30'

Direction of North and 1981 magnetic declination (MN) at center of map. Diagram is approximate.



SCALE 1 : 100,000

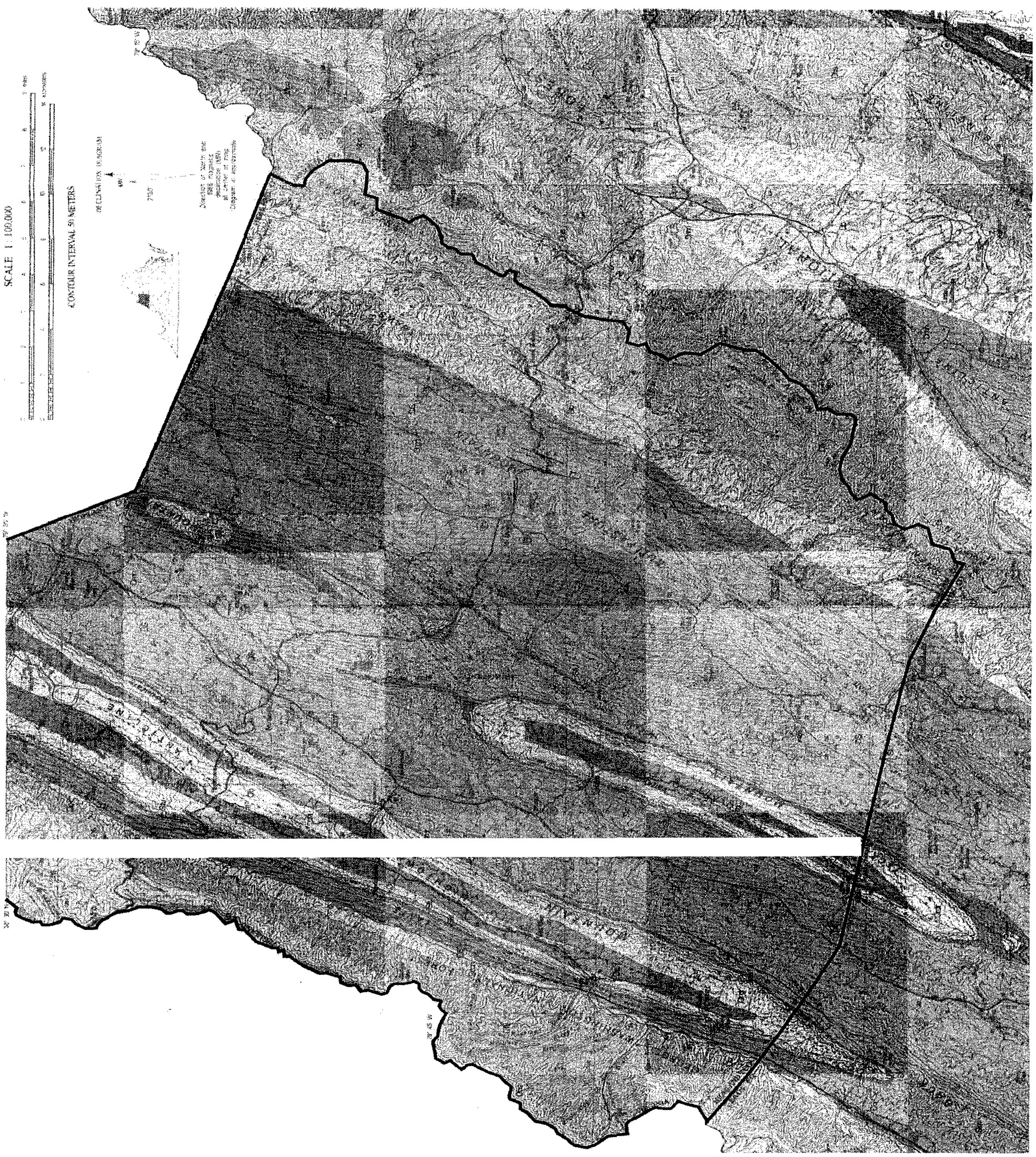
0 1 2 3 4 5 6 7 8 9 miles

0 2 4 6 8 10 12 14 kilometers

CONTOUR INTERVAL 50 METERS

Digital conversion in cooperation with the Department of Geology, College of William and Mary, Williamsburg, Virginia

Map prepared in cooperation with the U.S. Geological Survey - STATEMAP Assistance Award Number 98HQAG2011


SCALE 1:100,000
CONTOUR INTERVAL 50 METERS
DECLINATION DIAGRAM

APPENDIX C- GEOLOGIC TIME SCALE

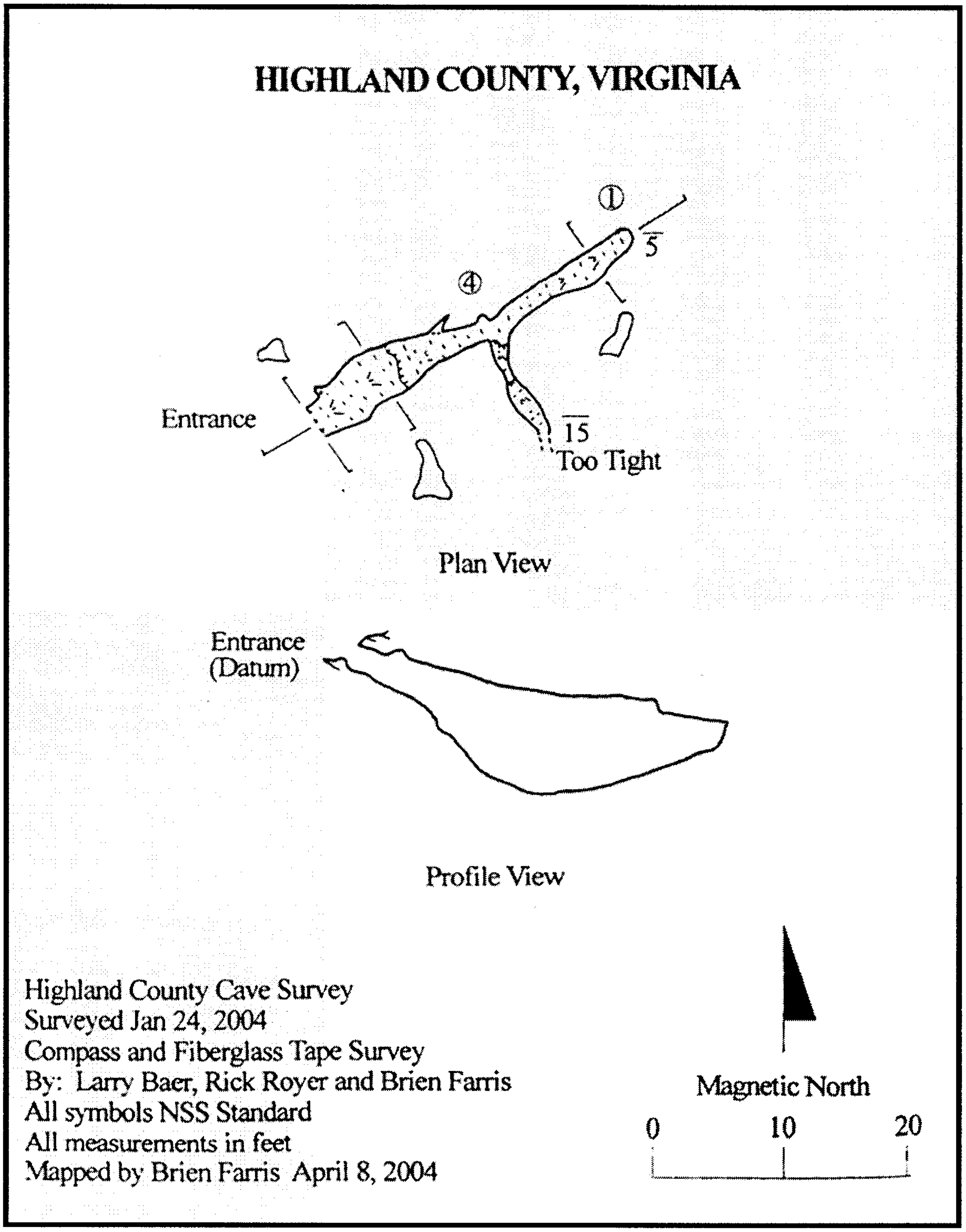
Geologic Time Scale

Era	System & Period	Series & Epoch	Some Distinctive Features	Years Before Present
CENOZOIC	Quaternary	Recent	Modern man.	11,000
		Pleistocene	Early man; northern glaciation.	1/2 to 2 million
	Tertiary	Pliocene	Large carnivores.	13 + 1 million
		Miocene	First abundant grazing mammals.	25 + 1 million
		Oligocene	Large running mammals.	36 + 2 million
		Eocene	Many modern types of mammals.	58 + 2 million
		Paleocene	First placental mammals.	63 + 2 million
MESOZOIC	Cretaceous		First flowering plants; climax of dinosaurs and ammonites, followed by Cretaceous-Tertiary extinction.	135 + 5 million
	Jurassic		First birds, first mammals dinosaurs and ammonites abundant.	181 + 5 million
	Triassic		First dinosaurs. Abundant cycads and conifers.	230 + 10 million
PALEOZOIC	Permian		Extinction of most kinds of marine animals, including trilobites. Southern glaciation.	280 + 10 million
	Carboniferous	Pennsylvanian	Great coal forests, conifers. First reptiles.	310 + 10 million
		Mississippian	Sharks and amphibians abundant. Large and numerous scale trees and seed ferns.	345 + 10 million
	Devonian		First amphibians; ammonites; fishes abundant.	405 + 10 million
	Silurian		First terrestrial plants and animals.	425 + 10 million
	Ordovician		First fishes; invertebrates dominant.	500 + 10 million
	Cambrian		First abundant record of marine life; trilobites dominant.	600 + 50 million
	Precambrian		Fossils extremely rare, consisting of primitive aquatic plants. Evidence of glaciation. Oldest dated algae, over 2,600 million years; oldest dated meteorites 4,500 million years.	

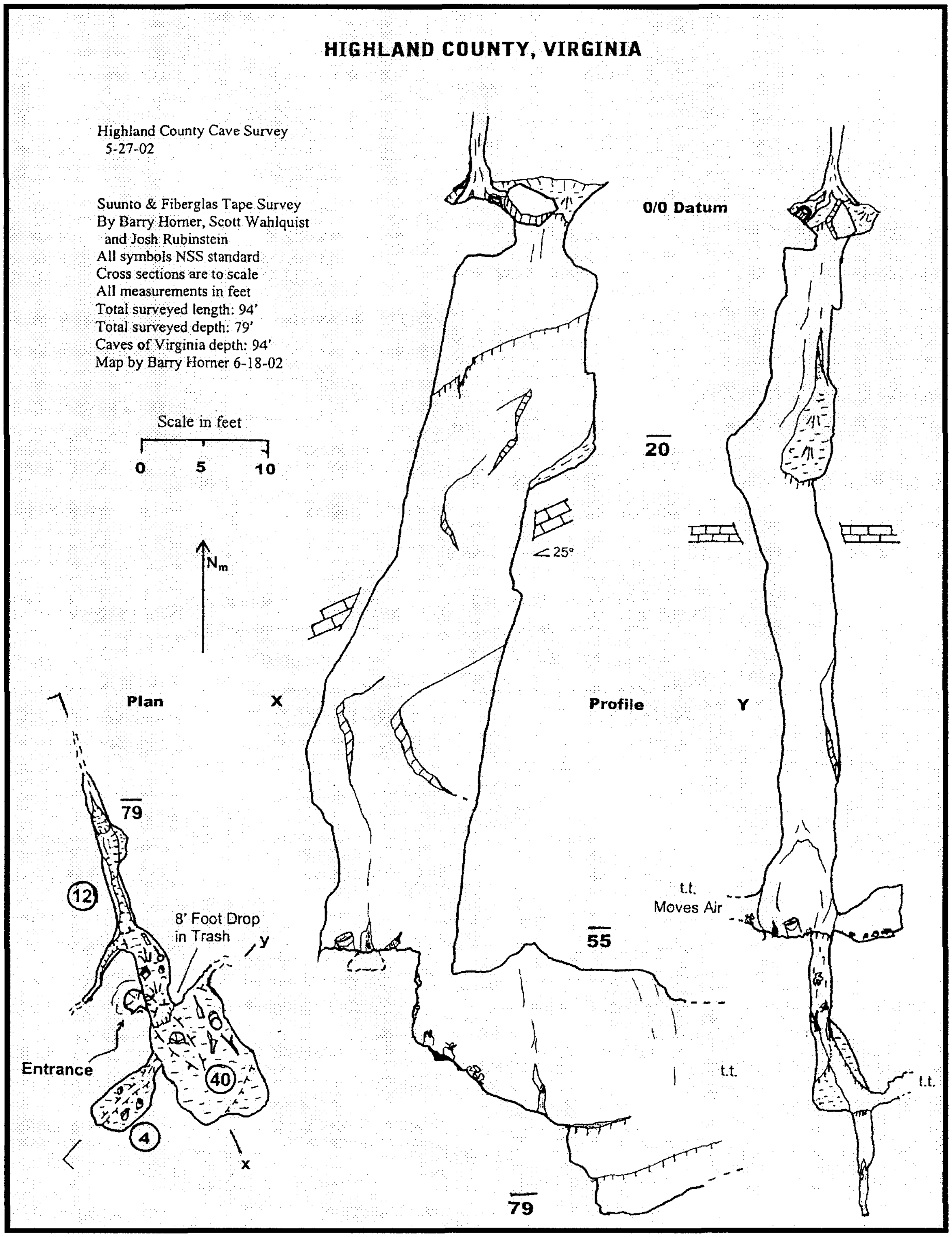
Center for Science, Mathematics, and Technology Education (CSMATE)
Colorado State University

http://www.csmate.colostate.edu/cltw/cohortpages/viney/nh_geologic_time_scale_large.gif

APPENDIX D- CAVE MAP SHOWING FISSURE PATTERN



APPENDIX E- CAVE MAP SHOWING SLOT FISSURE PATTERN



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